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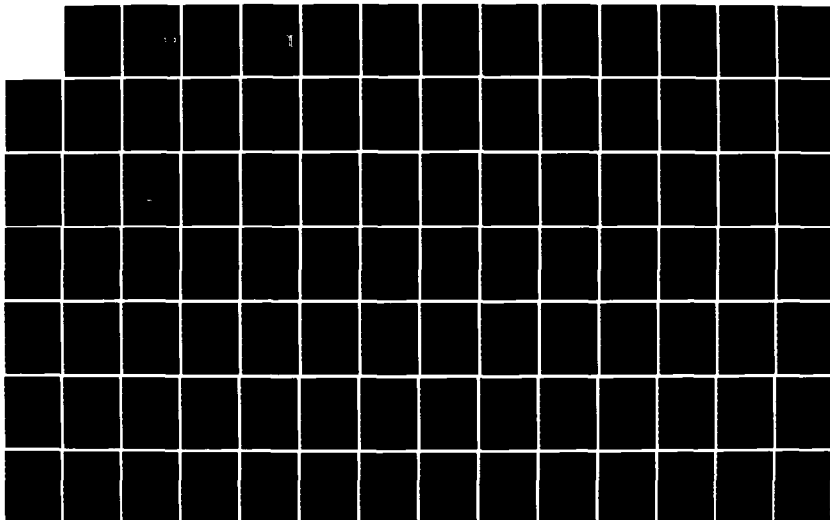
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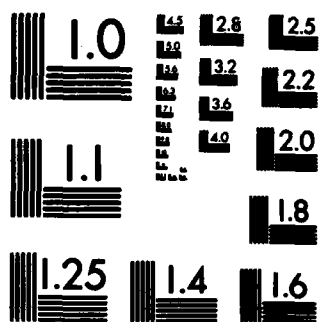
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PRINCIPLES OF ECONOMIC EFFICIENCY APPLIED TO
HIGHWAY INFRASTRUCTURE PROBLEMS

by

George E. Walrond
B.S., United States Air Force Academy
(1975)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE
DEGREE OF

MASTER OF SCIENCE
IN CIVIL ENGINEERING

at the

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May 1984

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Signature of Author George E. Walrond
Department of Civil Engineering
May 14, 1984

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Thesis Supervisor

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PRINCIPLES OF ECONOMIC EFFICIENCY APPLIED TO
HIGHWAY INFRASTRUCTURE PROBLEMS

by

GEORGE E. WALROND

Submitted to the Department of Civil Engineering
on May 14, 1984 in partial fulfillment of the
requirements for the Degree of Master of Science in
Civil Engineering

ABSTRACT

~~Research was made to determine the nature of the nation's highway infrastructure problem. It was determined that the nation's highways are aging without the required levels of rehabilitation, and the process is being accelerated by overloading, due primarily to the unpredicted levels of growth in the heavy trucking industry. Likewise, planning response to the problems of highway congestion in urban centers has been lacking. To further aid in the understanding of highway decay, the basics of highway design are reviewed and the modes of highway failure are discussed. This thesis proposes~~ ^{revealed} ^{also}

It is proposed in this thesis that the rules of optimal peak load pricing and economic efficiency be used to solve the urban infrastructure problems. The established rules of optimal peak load pricing are expanded to cover the costs of highway deterioration from traffic loading as well as the user costs of congestion. A comprehensive pricing formula is developed ~~in this thesis~~ and the long run highway investment rules are established.

The Boston Central Artery reconstruction project is used as an example of how to apply this theory in practice. In view of current technological advances in electronics and computers, it is proposed that this economic process could be applied in a real world environment.

Thesis Supervisor: Dr. Clifford Winston

ACKNOWLEDGEMENTS

I was motivated to study the national highway infrastructure problem by two forces. First, was the inspiration given by Professor Clifford Winston in his class, The Economics of Project Evaluation. Secondly, as an Officer in the United States Air Force, I am very interested in learning how to evaluate large government spending projects. The combination of my interests with that of Professor Winston led to this work. Throughout my research Professor Winston provided invaluable guidance and assistance, and I am very grateful for his help.

I would like to dedicate this paper to my wife Anna and my daughter Charli Jane who was born two months before the completion of this thesis.

Cambridge, Massachusetts

May 14, 1984

George E. Walrond



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INTRODUCTION

PURPOSE

The purpose of this thesis is to generate an urban road system pricing model. While the background research for this model will be academic in nature, the model will be constructed in a pragmatical manner. The ultimate objective is to provide a framework that is both understandable and which can be used in a real world environment.

PROBLEM

Currently there are two problems with pricing formulas generated to date. The first problem is that the pricing studies have been user oriented, that is, dealing with problems of congestion. The current situation with many urban roadways suggests that user oriented pricing is inadequate because there is a high degree of system decay and failures beyond congestion. The other problem is the inability to implement pricing strategies once proposed.

There are three reasons that implementation has been difficult. First, there has not been a clear definition of system revenue needs. Secondly, the problem of what to charge each user class has not been fully resolved. Finally, there are problems with the revenue collection process, a problem that may soon be solved by new electronic tolling technology.

SCOPE

This thesis will limit its focus to those highways, roads and streets comprising the primary and secondary arterials and collector streets of an urban highway system. The first section of this thesis will be broken down into two parts. First, Chapter One will identify the source and magnitude of the highway infrastructure problem in the United States. Then the basics of road building and highway structural failure modes will be discussed in Chapter Two. The thesis then turns to highway economics. Highway costs are summarized in Chapter Three, and Chapter Four formulates the investment strategy for an urban highway system and develops a highway pricing formula. Chapter Five demonstrates how this model could be applied to the Boston, Massachusetts regional area. The final chapter is a commentary on the real world application of this model, its value in public highway policy making, its limitations and the impact of future technology on optimal pricing of highway facilities.

CHAPTER 1

THE INFRASTRUCTURE PROBLEM

1.1 PROBLEM IDENTIFICATION

As the decade of the 1970's came to a close, the hottest issue in civil engineering was the status of the nation's infrastructure, or the health of the underlying framework that supports much of the nation's quality of life. This thesis deals with the highways, roads and streets which are part of the urban infrastructure. Throughout history there has been catastrophic failures in the United States highway system. An example occurred in the early 1970's when New York City's West Side Highway (built in the 1930's) collapsed. The most recent failure occurred in June, 1983 when a span on Interstate 95's Mianus River bridge failed, causing several fatalities when a large section of the bridge fell into the river. The Mianus River bridge failure was perfectly timed to highlight what the news media had been telling the nation, and that is the nation's infrastructure is in a serious state of decay.

In August, 1982 "Newsweek Magazine" featured an extensive report titled "The Decaying of America." This subject has also been highlighted often on the major television networks' news. This media hype, while subject to debate, has had a certain effect on the public's view of these issues. First, it has shown every citizen, lawmaker and others responsible

for public decision making that this is a national dilemma, and not one that is concentrated locally or regionally. This implies to everyone that the demands for federal funding to solve local infrastructure problems will be great. No doubt then, the competition for federal grants could be fierce if revenues are limited. Secondly, the media has indicated the infrastructure problems are going to cost huge sums to fix. For example, to quote "Newsweek", "All told, the cost of needed repairs around the country could run as high as \$3 trillion." (6:12) This is a staggering figure which may or may not accurately describe the magnitude of current problems, but certainly serves as a motivation to take a closer look at these problems. In addition, the problems that many urban drivers experience daily, such as congestion, worn out roads and posted bridges serve as vivid reminders of the failings of the nation's road system.

1.2 HISTORICAL BACKGROUND

Why does it appear that the highway infrastructure problem has surfaced overnight? Much of the answer lies in the history of the federal government's involvement in road building since World War II, and in the trends in general public capital investment since the mid 1960's.

Prior to World War I road building, ownership and maintenance were the domain of the states. The federal government's Bureau of Public Roads (BPR) served as a promoter of road building, a research center and an advisor to state and local highway departments. Care was taken at the federal

level not to trespass on the states area of highway responsibility. Federal financial aid began as an attempt to improve rural roads in order to enhance the mail service in isolated areas. These investments had other benefits such as enhancing farm product delivery to markets and allowing urban dwellers the chance to make pleasure trips into the countryside. These three factors, agrarian use, mail service and pleasure trips, all played an important role in raising the public's desire for better roads. Consequently, federal aid appropriations grew. There was also a growing number of advocates of a national system of roads. The compromise between these advocates and proponents of state ownership was the Federal Aid Highway System. States were asked to designate highways which were of national importance, with the total mileage being fixed in 1921 at 200,170 miles. (1:108) Federal funds were designated to be concentrated on this Federal Aid Highway System, but the federal influence was relegated to the role of financial supporter. The total mileage grew steadily, and in 1945 there was 308,741 miles in the system; none of which were urban roads. (3:279) This was nine per cent of the 3.3 million total miles. (3:205) There was no designated interstate highway system, and 48% of the nation's total road mileage was unsurfaced. It is also important to point out that of the 225,623 miles of urban highways, 81,242 miles or 36% were unsurfaced mileage. (3:205)

World War II had also highlighted another highway need, and that was a good system of roads to support military logistics during wartime. During WWI many miles of important

roads were decimated by overloaded trucks hauling materials to support military and civilian needs. The increased civilian trucking resulted from the saturation of the nation's railcar capacity by the war effort. During both wars load limit restrictions were reduced or eliminated with deleterious affects on road pavements. Lack of road capacity in certain key military supply areas was also a major problem in both wars.

In addition, military officials returning from Europe after WWII had witnessed first hand the effect that the German autobon system had on supporting the Nazi war effort and industrial growth. These officials realized how great an asset a good national road system could be. No doubt, similar impressions were left on returning servicemen who were entering civilian life, and who would later be amenable to political entreaties for a national highway system. Finally, one of the returning officials, General Eisenhower, became President in 1953 and was an ardent supporter of the "Grand Plan" for national highway development. It was during President Eisenhower's term in office that the nation embarked on the largest highway development plan in the country's history.

The Federal Aid Highway Act and Highway Revenue Act of 1956 had two major impacts on the nation's road system. First, the Interstate Highway System was to be treated as one huge project that was to be completed in 13 years. Secondly, federal highway user funds were earmarked for federal highway aid. (1:173) The effect of the first impact was to build many miles, or an entire system, in a short period

of time. The effect of the revenue legislation was to change the financial relationship between the states and the federal government; with states gaining more money, but losing flexibility on how this money was to be spent.

The Interstate System was actually begun prior to 1956, with the first official designation of mileage in 1950. Some of this mileage was in place and other mileage was being developed through turnpike systems in various states. At the same time, money was being spent on the nations primary and secondary system. The post war recovery was rapid, and was accompanied by a growth in automobile production of three million cars from 1945 to 1948 and a 22% increase in vehicle registrations. (1:154) The consequences in urban areas was a growth in congestion due to a serious lack of capacity and structurally deficient roads. The repair and expansion of the urban road systems went hand in hand with the Interstate Highway System development. Urban beltways that were designed as an integral part of the Interstate System have served as important feeder routes to urban areas.

The ratio of nonsurfaced to surfaced highway mileage during the years from 1945 to 1975 is an indicator of the level of construction during that time frame. Figure 1.1 depicts the national trend of this ratio for total highway mileage and municipal mileage. The total mileage showed the most significant drop in this ratio from 1945 to 1960, while the municipal ratio dropped significantly from 1945-1955. Likewise, the change in total surfaced mileage reflects the amount of new pavement placed in the same period.

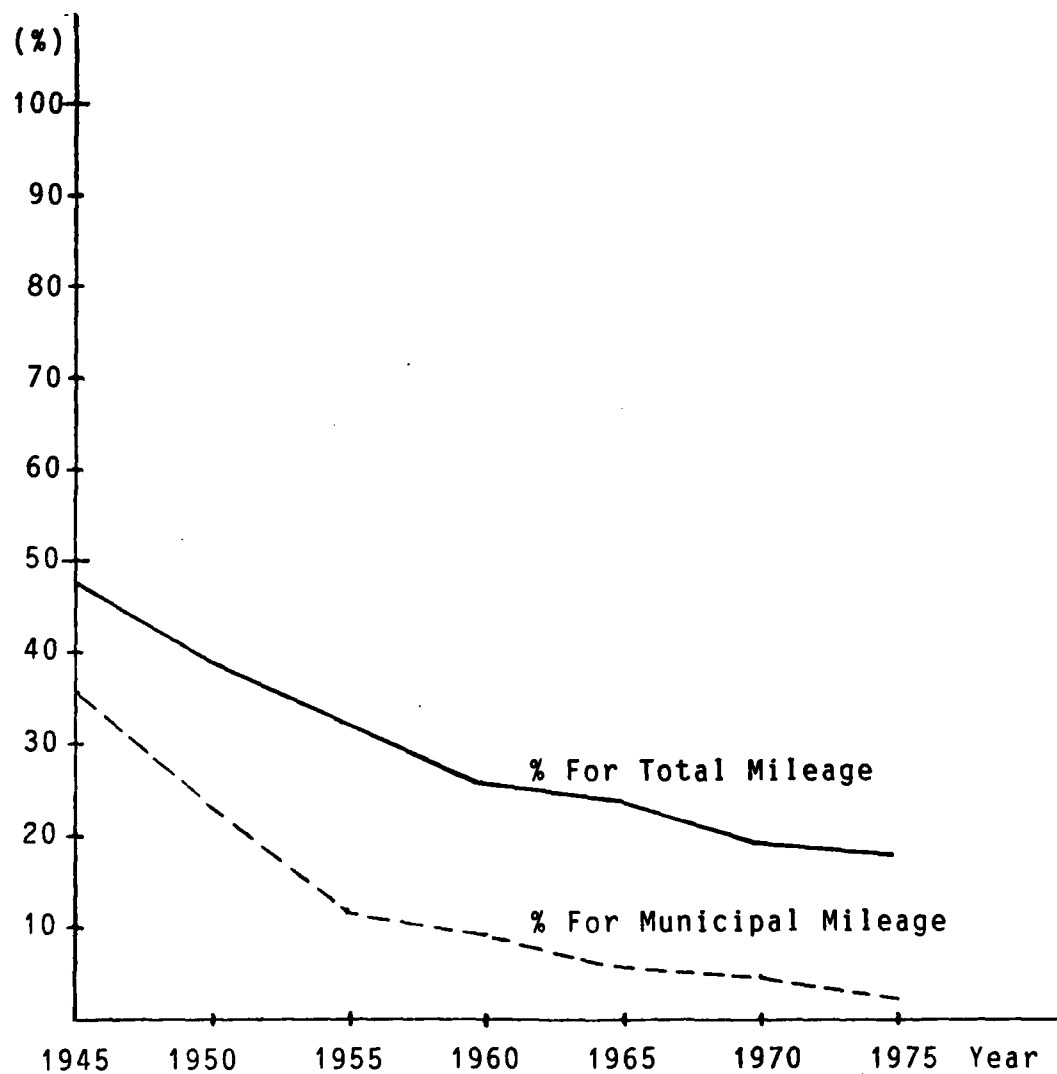


FIG. 1.1 PER CENT NONSURFACED TO
TOTAL NATION MILEAGE (3:205-211)

Nationally, the growth has been from 1.7 million miles to 3.1 million miles for all paved roads, while the growth in municipal mileage has been from 225,623 miles to 617,349 miles. Municipal mileage has expanded at a fairly constant rate, but the total paved mileage showed the greatest change between 1945 to 1960. These trends in paved mileage are shown in Figure 1.2. Figure 1.3 is a graph of the total highway mileage in the United States during the same period. A comparison of all of this data shows that during the 30 year period from the end of WWII to 1975 a significant amount of road upgrading was taking place along with new construction.

Simultaneously, road geometry was being improved by roads being straightened and having their grades improved, while some unsuitable roads were abandoned. A Department of Transportation report to Congress states that "virtually all completed mileage is free from substandard design." (8:xviii)

To understand how this relates to the current infrastructure problem, the design life of highways and bridges must be evaluated. In general, highways are assumed to have a life of 20 to 30 years. The city of Cincinnati's Public Works Department uses an estimate of 10-15 years for the life of a road before major resurfacing is required. (6:19) Oakland uses a 25-30 year lifespan. (5:19) Using 20 years as a basis and referring to Figure 1.2, it can be seen that the period 1965 to 1985 can be considered as the window when a substantial portion of the nation's highway mileage would be scheduled to wear out, and this is the phenomena that is occurring now.

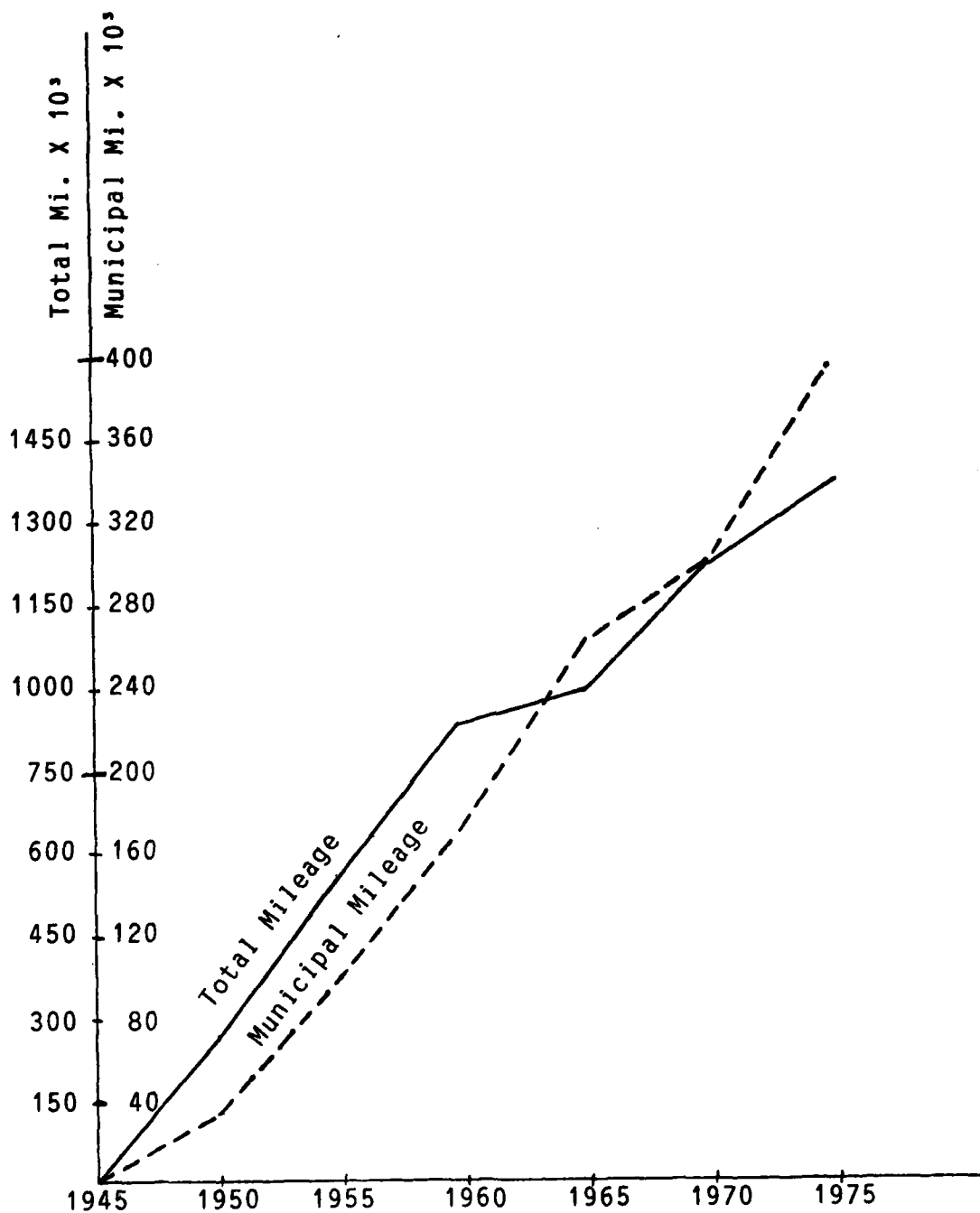


FIG. 1.2 GROWTH IN PAVED MILEAGE (U.S.) (3:205-211)

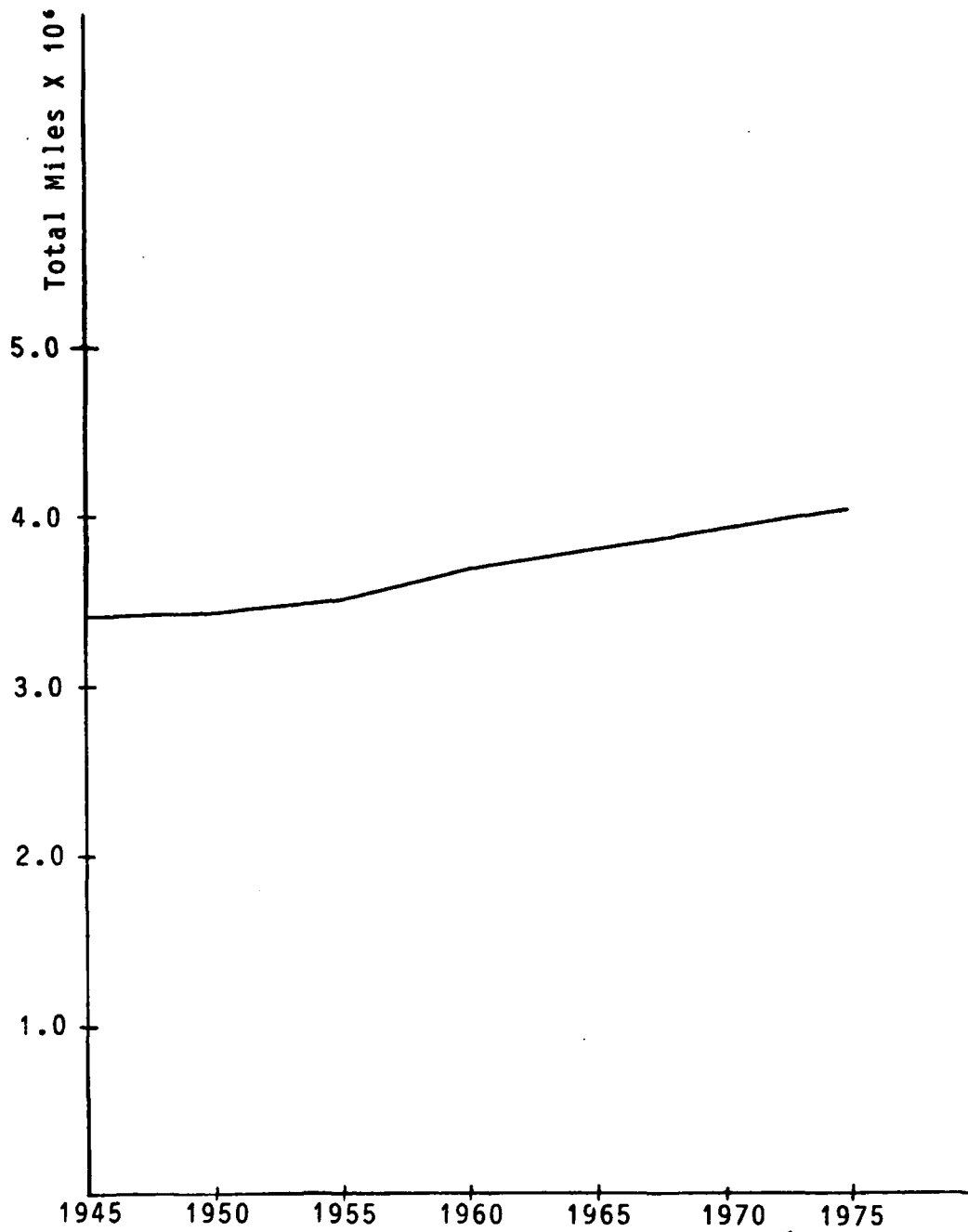


FIG. 1.3 TOTAL HIGHWAY MILEAGE (3:205-211)

In addition, there is evidence that there are significant levels of bridge decay. A 1981 federal government bridge report shows that, of the 557,516 bridges inventoried nationwide, 126,655 were structurally deficient and 121,872 are functionally obsolete. (4:4) It is worth pointing out that 44,900 bridges are on the Interstate Highway System, implying that most are less than 25 years old. Despite this, 12% of the Interstate Highway System bridges are listed as deficient. (8:87) Nationally, 348,014 or 63% of the bridges are less than 40 years old, leaving a substantial number of bridges that are nearing or have exceeded their design lives. (4:8) Bridge failures have a high potential for being catastrophic, and will disrupt traffic flows for a long period of time. This makes the national bridge problem worthy of urgent attention, even though the bridges overall are not in as bad shape as the nation's roads. The above statistics also show that the bridge actual life is highly variable, though it has generally been assumed to be around 50 years.

Up to this point it has been shown that roughly one third of the nation's highways are at the end of their expected design life. This figure does not include the mileage in place prior to 1955. Also, the newer mileage, built since 1965, is approaching critical maintenance milestones as well. As yet, highway operational and maintenance policy has not been discussed.

1.3 OPERATIONAL POLICY

At present the federal government will pay for 90% of the construction costs of road projects in the Federal Aid

Highway System. Highway operational and maintenance responsibility belongs to the states. In an urban setting operational ownership of the roads and highways in a city could fall under local, county, district or state responsibility. This forces a lot of diversity in operational policy in cities. Regulation of vehicles is one area of diversity. Even though states are required by federal mandate to have load limit standards for vehicles, enforcement of this policy has varied nationwide.

Maintenance policy has also varied. The periodic capital investments required to keep a certain level of service on a particular road has in many cases been deferred. The direct affect is to shorten the life of the road. Nationally, when inflation is included, the highway investment in capital improvements has fallen from \$9.8 billion in 1967 to \$5.0 billion in 1979. (8:16) The inflation of maintenance costs have strained highway budgets which are already competing with other capital investment budgets such as water and sewer. In some cities, such as New York and Boston, maintenance activities have actually been deferred. This type of policy has been most prevalent in cities which have experienced a sluggish or declining economy, a shrinking population and a declining tax base during the late 1960's and 1970's. The highway demand did not shrink proportionately since commuting into these cities still kept daily highway use up. As a general observation, the maintenance of a highway system tends to be tied to the economic well being of a locality. This could be expected in view of the federal

policy towards road financing. Currently, most federal money to cities comes from urban redevelopment grants. The disbursement of funds to a particular urban area's needs is done locally. While no conclusion is being drawn about this policy, this federal money is often never invested in the city's highways.

It can be concluded that the stage has been set for a nationwide highway decay problem on a massive scale. The degree of highway and road system deterioration is dependent upon the historical maintenance and traffic load trends of each road. Even with a good operational and maintenance record much of the Federal Aid Highway System has reached the stage where rehabilitation and reconstruction is required. In addition, for those highways, roads and street systems where congestion is a problem there is little hope for relief because of the increasing growth in vehicle miles traveled (VMT) annually. The projected growth in VMT from 1977 to 1995 is 157% with increases in every class except large cars, with combination trucking (Gross weight > 50 KIPS) showing an annual 3.17% rate of growth. (2:IV-31) Therefore, in addition to solving the highway and bridge deterioration problems, the additional traffic loads, particularly in heavy trucking, must be dealt with.

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CHAPTER 2

HIGHWAY PLANNING BASICS

2.1 BASIC DESIGN DESCRIPTION

This chapter gives a brief description of the engineering involved in road design. The road failure modes will be discussed and, finally, the urban road system dealt with in this thesis will be described. The intent of this chapter is to lay the basis for understanding the physical aspects of a road and highway system and the magnitude of scale of the system being dealt with.

Economists and engineers must always keep in mind the basic reason why roads are built. The fundamental objective of highway policies is to transport vehicular traffic efficiently, safely and at the greatest economy to the owners and users. Efficiency implies that the road is smooth enough and laid out in such a manner that traffic can travel at an optimal speed. Safety includes many things such as road lighting, superelevation, signs, etc., all of which add to the cost of the system. Safety also requires adequate road capacity for the level of traffic. Economy addresses three areas. The first is the highway's need when compared to alternatives. Second is the requirement to select the best design, a process which is a systems analysis problem. The final area is economy to the user.

The basic function of the road itself is to transmit the vehicle's load, both dynamic and static to the earth's crust. Road building always begins with excavation that limits grades, provides an increased line of sight and removes material with unsuitable road bearing qualities. After excavation is complete, the soil remaining is called the subgrade. If the subgrade is comprised of soil with unsuitable load bearing characteristics and further excavation or filling is uneconomical, the soil can be stabilized by mixing in lime or cement. The subgrade is covered with a base course of course aggregate or sand. The base is usually a single layer ranging from a minimum of 6 inches in thickness up to 20 inches depending on subgrade conditions and climate. Often economy and design may dictate a two level base course. Grading criteria depends on the strength requirements, economy and, most importantly, drainage requirements. The base is then covered with a pavement made of a bituminous aggregate mix or concrete. Figure 2.1 shows what the system has to accomplish as far as transferring loads are concerned. Figure 2.1a depicts the distribution of load pressures throughout the roadbed showing that the contours of highest stress are closest to the road surface.

The paving material is classified as rigid or flexible. Flexible pavements do have the strength to carry high vertical loads, but do not respond well to bending. In order to prevent permanent deformation, cracking or fatigue, the road base must be deeper and have good durability. The subgrade has to be good material or stabilized. Rigid, or concrete pavements, can carry heavy vertical loads and resist bending. Rigid

pavements are good because they reduce the base depth and can provide good load distribution for inferior subgrade material. Flexible pavements are generally 5-6 inches thick while rigid pavements are 8-10 inches thick.

Flexible pavements provide a smooth, continuous riding surface and can make excellent waterproof covers for the road base. Flexible pavements can be designed to drain water (open mix) to provide a surface with good skid resistance. Rigid pavements, while strong and durable, in general are more expensive and depending on construction method, will cause road noise and roughness. If the pavement is unreinforced, the pavement must have crack control joints at frequent intervals (15-20 feet). This joint spacing can be increased up to 100 feet with light reinforcing and eliminated with heavy continuous reinforcing. At points where new pours begin, expansion joints must be placed. Concrete will develop cracks from shrinkage, vertical shear, tensile stress and compression failure.

In order to perceive the magnitude of scale involved in road construction, some standard road dimensions will be given. The accepted lane width is 12 feet for roads carrying a mix of car and truck traffic. Road shoulders width are traffic density dependent, ranging from 4 feet to 12 feet wide. In addition, highways with multilanes of traffic traveling in one direction usually have a separating medium between opposing directions of traffic, the width of this separation varying from 0-60 feet in urban areas. (8:298-303) City streets are also designed with parking lanes and sidewalks. Table 2.1 is a summary of these basic road dimensions.

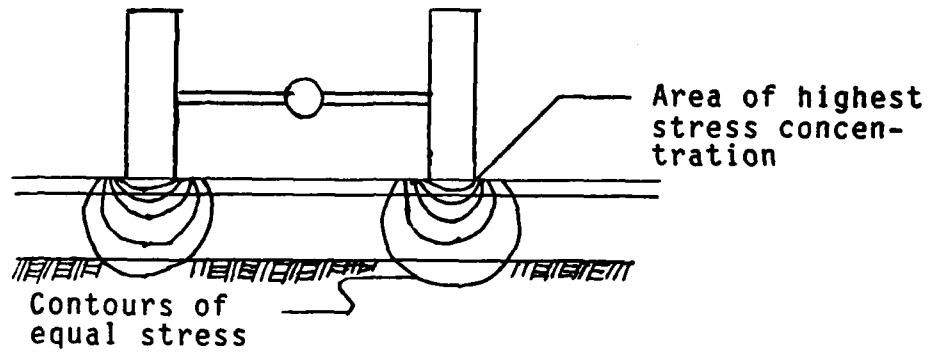


FIG. 2.1a

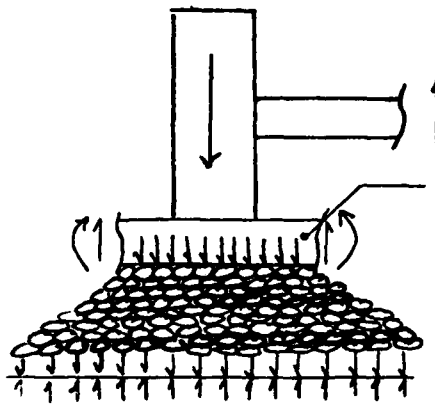


FIG. 2.1b

FIG. 2.1 ROADBED LOADING

TABLE 2.1 TYPICAL ROAD DIMENSIONS

<u>Item</u>	<u>Dimension</u>	
Base Course Thickness	6-20	inches
Pavement Thickness		
Flexible	5-6	inches
Rigid	10	inches
Lane Width	12	feet
Shoulders	4-12	feet
High Speed 4-Lane Arterial (Total width not including drainage or right-of-way requirements)	156	feet

It can be concluded that publicly owned land acreage for road systems is immense. The volumes of building materials used in road construction is huge. Public land ownership removes the given property from the real estate tax base, and the benefits of public use of its land must be weighed against the opportunity costs of both public and private alternative uses. Because the magnitude of materials and labor requirements can be so large, the impacts of highway investments and construction can easily create ripple effects through a regional and national economy and the construction industry.

2.2 VARIABILITY IN DESIGN

One of the issues that makes any study or design of highways so enigmatic and complex is the high amount of variability in many of the design factors. This includes the areas of estimating needs, financing, and engineering

design. The problem is first encountered when planners attempt to define highway needs. These needs could be based on a subjective requirement, or the needs could be defined by empirical evidence. A subjective requirement would be based on a line of thought that believes that highway investments would enhance a local area. For example, a small city attempting to capture part of a regional economic growth would feel that improved highway facilities would attract businesses. The use of improved highway transportation to revitalize an aged urban center is another example of subjective planning. While evidence may show that highway investments in other cities have accomplished the two above objectives, it really says nothing concrete about a specific city. Objective planning, on the other hand is based on clear evidence facing the highway planner. Highway congestion and street decay are examples of this evidence. In both cases, objective and subjective planning, a degree of forecasting and prediction is required.

Population trends nationally have indicated a continued growth since the U. S. Census was first taken. While this has been true for the nation as a whole, it does not always hold up for every locality. Cleveland, for example, suffered a 14% loss in population in the 1960's. (6:4) Boston, from 1950 to 1970, lost a fifth of its population. (4:3) Dallas, on the other hand, has been a city of growth as indicated by both an expanding tax base and population. (7:4) Demographic trends serve the forecaster best in the short run,

but become subject to variation which tends to grow over time. To put this into perspective, the short run would be a five year time span and the long run would be a period greater than 10 years. Since highways are usually designed to last 20 to 30 years and bridges 50 years, highway planners must deal with long range forecasting.

Some historical examples serve to show the difficulties associated with properly identifying highway needs. One of the problems facing highway engineers in the period from 1920 through WWII was the inability to keep up with the demands of the motoring public. The following quote by Federal Highway Administration (FHWA) historians describes the problem.

"As the roads improved, the annual usage per vehicle increased, so that highway traffic built up faster than vehicle registrations in a self reinforcing spiral. The highway system never reached maturity. The need for capital expenditures did not diminish, but increased enormously." (1:163)

This type of problem may still exist as indicated in a Department of Transportation (DOT) report that states:

"The Interstate was designed and constructed based on travel forecasts that underestimated the enormous popularity and use of the system, particularly the growth of the long distance trucking industry." (9:78)

The above examples point out that there is a major difference between forecasting and prediction. Forecasting is the science of saying, within a range of certainty, what the nature of certain elements will be in the future. Prediction, on the other hand looks at cause and effect relations.

The second area of variability is financing. The selection of the appropriate discount rate, the prediction of revenue generation capability and inflation stand out most prominently. Variability in economic terms greatly impacts investment decisions such as the decision to build or not to build, design selection and operational policy. These influences are continuous throughout the life of the project, with the potential for wide variation over time.

Engineering problems host other areas of variability as well. Two areas exhibiting a high degree of uncertainty are loading estimates and soil conditions. Another area beyond the control of the highway designers are operational (traffic and weight constraints) and maintenance policies used after the road is turned over to the road owning authorities.

The heterogeneous mix of traffic on modern highways makes pinning down the design loading conditions difficult. Vehicle weights vary from 2,500 to 80,000 pounds. Therefore, the design method has to incorporate a means to compare the effects of each class of vehicle on road usage. For example, statistics may show that the traffic mix per unit of time on a given highway is 35 cars (avg. GW=3,500 lbs), 10 trucks averaging 8,000 lbs, five tractor trailers weighing 60,000 lbs and a single tractor trailer which weighs 80,000 lbs. Would a road designed for the heaviest vehicle stand up under the repetitive loads of the lighter but more numerous cars and trucks? One widely used method of design that attempts to answer this type of question is the use

of equivalent single axle loads (ESALs). Peattie describes ESALs as, "The concept of equivalent load means that an application of a load (ℓ) is equivalent in terms of pavement damage to (F) applications of a standard load (ℓ_s). . ." (3:10) The standard load most used is 18,000 lbs. The effect of these loads on a given road's subgrade is not easily predicted.

Designers will have a survey taken of the conditions of the soil upon which a road will be built. Soils surveys are expensive, but despite the degree of survey intensity, the final report on soil conditions is still a geotechnical engineer's best estimate of existing conditions. These conclusions are based on a study of field surface conditions, borings, soil sample testing and test pits. The more extensive the investigation, the more certain the estimate. As Table 2.1 shows, the area of investigation is very large, and funding a thorough geotechnical study would be very expensive, and often the designer is given results with a high degree of uncertainty. The end result is that highways develop localized areas of failure where the design was inadequate for the actual conditions. To account for this, the pricing formula developed in this thesis allows for charges of routine maintenance on an annual basis, and this maintenance should fix these types of failures.

Finally, the area of engineering risk must deal with operational policy after the road opens. The regulation of users and the maintenance of the facilities becomes subject to political forces. It is not being implied that the political process does not make decisions based on the best

interest of the road system. On the contrary, it could be argued that a rational politician would indeed be cognizant of the importance of protecting the public's investments. However, during the 20 year life of a road individuals and political bodies responsible for making road policy change often. In addition, social needs and spending priorities change. For example, the City of Boston, Massachusetts spent 261.1 million dollars for city school buildings during the period from 1962 to 1977 as opposed to 61.3 million dollars for city streets in the same period; a figure purported to be too low to adequately maintain the street system. (4:11)

A working pricing scheme is a means to provide a continuum in policy during the political changes. In addition, the revenues raised by the pricing and financing program can be retained by the highway operating agencies to support their road systems. In summary, the risk in highway engineering and operations is dealt with in the pricing formula developed in Chapter Four. Even though population and associated road use are beyond the control of highway planners, the design restrictions placed on a particular highway can be controlled to a large degree through pricing, vehicle registrations and law enforcement.

2.3 HIGHWAY STRUCTURAL FAILURES

Subgrade Failure

There are many minerals and substances in the earth's crust, but for the purposes of soil mechanics, they can be broadly classified into two groups, rocks and clays. Rock

breaks down into gravel, sand and silt. Silt fines are microscopic in size and only slightly larger than clay particles. In some ways, silt behaves like clay particularly in its response to water. In addition to the above constituents of soil there is organic matter which is unsuitable as a load bearing material and is usually removed from a road's subgrade.

A unit volume of soil consists of solid material, water and air voids. The size of the voids is largely dependent on the soil type and any compaction or consolidation influences. The network of voids form a series of capillary tubes that have an important effect on soil behavior. A completely dry soil supports loads through a series of particle interlocks. If the voids are small, the introduction of water will help bind the soil through the meniscus action between adjacent particles and the air in the voids as shown in Figure 2.2. Air has to be present for this capillary tension to bind the soil particles together. As water fills

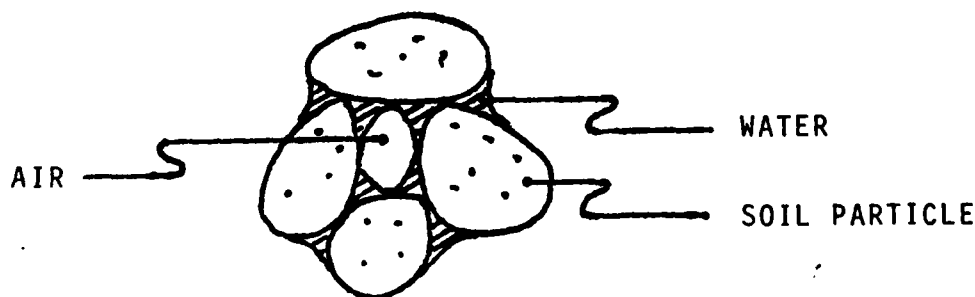


FIG. 2.2 CAPILLARY TENSION IN SOIL

the voids, displacing air, the capillary tension is reduced and the water builds up hydrostatic pressure. Drying a soil increases the capillary tension, pulling the soil particles closer to create shrinkage.

Water has a great effect on clay behavior. Clay particles are microscopic flat plates that carry a surface charge which will attract the water dipole and cations. Water close to the surface is held tightly and this bond decreases as the distance from the surface is increased. Dry clay particles will be attracted by edge charges, shared cations, hydrogen bonding and Van der Waals forces. These forces decrease rapidly as particle spacing is increased, and adding water has the effect of increasing particle spaces. Therefore, in the presence of excessive water, clay particles will flow and deform under a load with water acting as a lubricant to aid movement. The particle separation caused by adding water also causes clays to expand when wet. Confining clay particle movement and imposing a load will squeeze water out of the particles and increase particle attraction which causes settlement. Drying a clay as mentioned before will cause shrinkage, primarily due to capillary tension. Each type clay has certain load bearing qualities depending on mineral composition, particle shape, size and water content. Likewise, there is an optimal water content for compacting clay to a maximum density. When a clay subgrade is prepared, it is desirable to compact the clay to maximum density in order to maximize load bearing capability and minimize settlement. It is desirable to keep moisture out of the subgrade to maintain its stability.

A clay subgrade can fail in the following ways. Excessive moisture makes the subgrade plastic and the material flows from the point of loading. The displaced soil causes the pavement and base to settle and a rut is created. Constant pounding of a clay subgrade causes two effects. First, any clay particles not lying flat will tend to fall into a flattened position, decreasing the soil volume. Secondly, as moisture is squeezed out, the particles pull closer together. These two actions combined cause consolidation and settlement, causing the pavement and road base to settle. Drying shrinks the pavement and this alternating with wet swelling will cause pavement fatigue.

The primary means to protect the subgrade is to seal off water (a pavement function) and provide good drainage. Clays can be stabilized with cement or lime to reduce water effects. From an operational point of view, maintenance provides the greatest protection of clay subgrades by preventing water from seeping through pavement cracks and keeping the road drainage system working.

Rock, gravel and sand have excellent load bearing qualities, and these types of soils provide support from particle to particle interlocks. Gravel and sand fail under heavy loads by the particle corners that are in contact with other particles breaking. Sand and gravel in their natural state do not rest in the most dense configuration and are particularly susceptible to vibration loads. A combination of vibration and vertical loading will cause gravel and sand

to become more dense. In the subgrade, the settlement of sand and wearing of particles could cause road settlement, though not in any way as drastic as the failures in a clay subgrade. Most problems with sand subgrades occur in embankments where a high water table can cause sand liquefaction and a mudslide. More commonly, failures occur when there is a combination of gravel, sand and clay, with the clay playing the major role.

A common means of subgrade failure associated with rigid pavements is pumping, which occurs when a pavement section moves vertically around a crack or construction joint. In the presence of excessive water in the road base, the constant vertical motion due to traffic loading causes the water to churn up fine subgrade particles into a slurry that is ejected through the pavement crack. Eventually enough soil is ejected that a void is created which causes the base to settle. Without the base, the concrete pavement is weakened and further cracking and sectional breakup takes place.

Base Course Failure

Three primary modes of base course failure take place in addition to the subgrade failure mentioned previously. These are particle breakup, particle movement and frost action.

Particle breakup occurs from excessive loads and water action due to freezing. The expansion of frozen water in the microcracks of the aggregate simply causes particle breakup. Often designers specify an aggregate that has a high resistance to water penetration, but the locality of the road may

prevent use of this type of aggregate. As mentioned previously, high pressure on a gravel particle will cause breakage or crumbling at the points of contact between aggregate particles. Over time the corners of the aggregate will round off, and will lead to particle movement.

Aggregate roughness and corner sharpness are desirable properties of base course material, since this causes the particles to lock against each other and not move. Rounded aggregate will move easily under a load. As a roadbed is subjected to repeated loads which wears out the aggregate in the base course, the particles become displaced and leave a void or rut in the base. This will cause a flexible pavement to settle and a rigid pavement to crack.

Frost damage is one of the major causes of road damage and pavement failure, and is caused by the formation of ice lenses and water seepage into the base course. Water seepage into the base course is prevented through maintenance. Frost heave can occur even if the pavement is in good shape. If the base aggregate has a large percentage of fine material creating small voids, water will be drawn to the surface of the base course by capillary action. Water near the surface will freeze and any free molecules of water near the ice will be strongly attracted to the frozen particles. The combination of capillary action and the attraction of water to the ice particles causes a growth in frozen water which creates an ice lense. Pumping, which has been discussed, can fill the base course voids and contribute to the growth

of ice lenses. In order to prevent ice lenses, designers must specify an aggregate with large voids to a depth at least half the depth of the natural frost level.

Flexible Pavement Failure

Flexible pavement fails by rutting, cracking and disintegration. Pavement failures can be induced by roadbed failures or can fail even if the roadbed is functioning properly. Often a vicious cycle is created where a crack in the pavement causes roadbed failures which in turn enhance pavement failures.

Bituminous materials, asphalt, bitumen and tar, are very ductile, susceptible to plastic deformation and viscous at high ambient temperatures. These materials combined with graded aggregate make the flexible pavement material mix. Their primary function is to coat the aggregate and help it stick together or stay in place. The highway engineering term for this is stability. A coarse aggregate and a lean bituminous mix makes an open pavement which allows water drainage. A coarse aggregate and thick bituminous mix makes an impervious pavement that is susceptible to instability at high temperatures. Another problem with this type of mix is that traffic loads will cause the bituminous material to bleed from the mix which reduces skid resistance and can cause pavement rutting. A combination of 6-7% by total weight of asphalt and well graded aggregate makes asphaltic concrete. This mix is very stable, carries a high vertical load if properly supported, and subject to fatigue cracking.

Lab tests show that asphaltic concrete exhibits bending beam behavior, and develops both compressive and tensile stresses which under repeated loading induces fatigue cracking.

Disintegration is caused by aggregate separating from the pavement. The primary cause of disintegration is the displacement of the bitumen binder from the aggregate particles by water. Some aggregates have a greater affinity for water than bituminous binder, and, if water reaches the surface of an aggregate particle, it will cause the binder to peel from the particle. Tire friction eventually kicks these particles loose from the pavement.

Finally, there is a final mode of pavement wear called polishing. This phenomenon occurs over time, as vehicle tire friction smoothens the aggregate on the pavement surface and reduces braking.

Rigid Pavement Failures

Rigid pavement fails by cracking, spalling and blowing up. Microcracking of large concrete slabs is inevitable. As the concrete cures, it shrinks and tries to drag the entire slab inward. The strength of the curing concrete is not high enough to pull the weight of the slab and cracking occurs. Longitudinal and lateral steel reinforcing is used to prevent shrinkage cracks. Concrete pavements also act as a bending beam and the tensile stresses developed under loading also cause microcracks. Any crack will allow water entry, and in cold climates the freezing and subsequent expansion of this water will cause crack growth. In addition,

crack growth in concrete can be induced by the growth of salt crystals in microcracks. Eventually water and salts will reach the reinforcing steel and the resultant corrosion will also cause the concrete to break apart. The growth of microcracks into larger cracks and the flaking off of concrete particles from the pavement is called spalling. Even though spalling is most prevalent at high stress areas, it can occur anywhere and eventually lead to pothole development. Large cracks can also occur if the ultimate stress in shear and compression is exceeded. This occurs when excessive loads are imposed on a weakened pavement. Concrete expands and contracts due to temperature changes. If expansion joints are not created and reinforcing is inadequate, the heat induced expansion will cause the pavement to heave upward and crack. This is called pavement blowup.

Cracks in both rigid and flexible pavements are the real villains in road breakup. Whether due to design flaws, excessive loads or a host of other reasons, cracks are inevitable. Therefore, the only way a road can achieve its full design life at a high level of service is to have a sound maintenance program. Highway pricing must include the cost of this maintenance, and the revenues generated from highway users must be put into the maintenance fund.

2.4 PAVEMENT LOADS

There has been some debate over the real impacts of heavy trucking on pavement wear. In order to better understand this issue, the subject of pavement loading is introduced.

Figure 2.4 shows how the different stresses build up at a point in the road's surface as a wheel passes over the point.

Observations of highways with steep grades have shown that the uphill side of the pavement had more damage than the downhill side that had the faster moving traffic. This had led highway engineers to believe that static loads damaged roads more than moving loads. Recent studies have shown that this is not the case at speeds above 40 mph. (5:41-42) Static loads do affect the stability of flexible pavements more than dynamic loads, but, depending on load frequency, the soils natural frequency and roadbed damping, a moving load can actually amplify its static value. Table 2.2 demonstrates how rapidly forces can build up in the point shown in Figure 2.4. Some soils such as silt are very resilient.

TABLE 2.2 SPEED AND DISTANCE TRAVELED

Speed (mph)	Distance Traveled per Second (ft)
25	36.7
35	51.3
45	66.0
55	80.7
65	95.3
75	110.0
80	117.3
90	132.0

The situation can occur where the roadbed is bouncing back from the affects of a suddenly applied load and it is suddenly hit with another load, such as the front and back wheels of a tractor trailer passing over a point. The bouncing mass

is accelerated upward when it is hit with another suddenly applied load that tries to force the road mass downward. This has the affect of a head on collision between the wheel and the road, inducing even higher loads within the roadbed and pavement. If the stresses shown in Figure 2.4 are modeled as a symmetrical triangular pulse load and there were no soil damping, the maximum soil deflection due to the rapidly applied load would be 1.5 times greater than that caused by a static load. (2:42) Even though damping decreases this dynamic load factor, the Portland Cement Association has recommended load safety factors up to 20% over the static loadings to account for the dynamic response due to moving loads. (5:42)

If a highway is designed to carry heavy trucking, then lighter vehicles are apt to do less pavement damage, but even cars traveling on a high strenght superhighway must share the cost of pavement deterioration. Tests by the American Association of Highway Officials (AASHO) have been able to express single axle load damage in terms of an equivalent number of 18000 lb axle loads. This design technique was mentioned in Section 2.2 and Table 2.3 shows the relationship between the different single axle loads. This shows clearly that heavy trucking applies a substantially greater load than cars and have a highly destructive capability on worn pavements. Highways are designed to withstand a finite number of ESALs during the roads life. Because of this, the demand for highway usage can be expressed as ESALs per vehicle.

A wheel moving along a paved surface generates primarily vertical compressive stresses, but vertical shear and horizontal compressive stresses are generated at the same time. A rolling wheel builds up compression contours as shown in Figure 2.3.

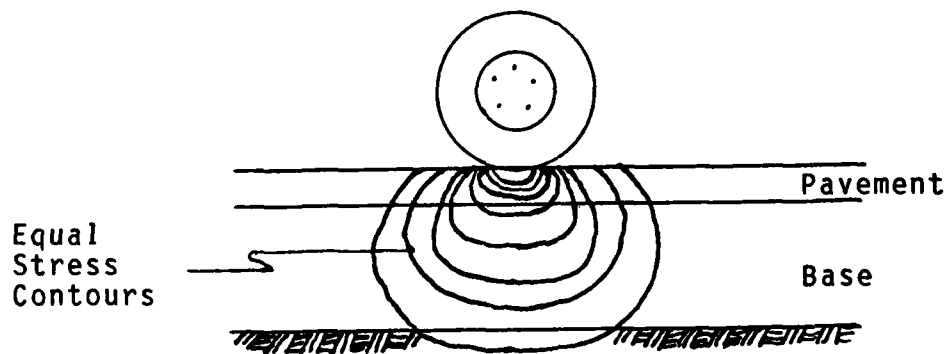


FIG. 2.3 VERTICAL PAVEMENT AND ROADBED LOADING

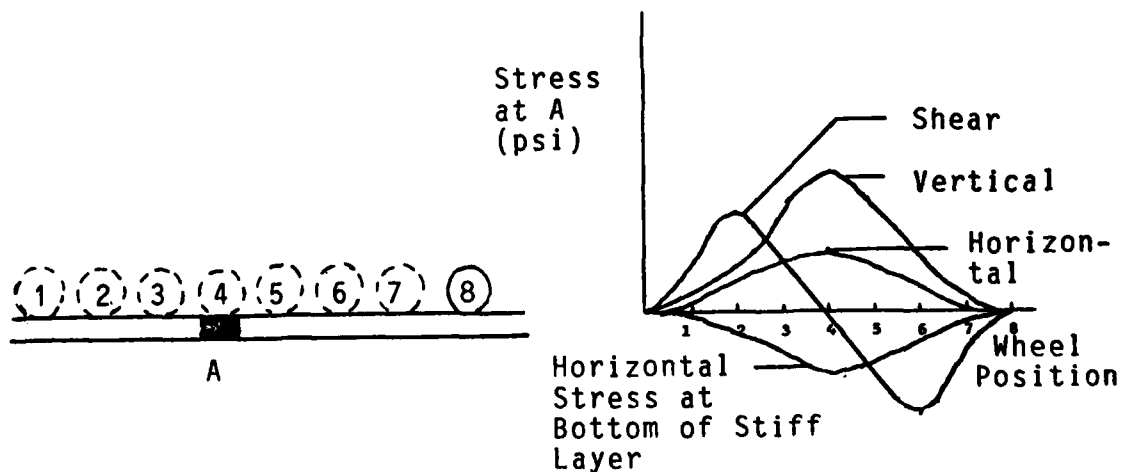


FIG. 2.4 POINT STRESS BUILDUP DUE TO MOVING LOAD (3:45)

TABLE 2.3 EQUIVALENT AXLE LOAD FACTORS

Single Axle Load (lbs)	Factor
4500	0.0039
9000	0.0630
13500	0.3160
18000	1.0000
22500	2.4410
27000	5.0600
31500	9.3800
36000*	16.0000
40500	25.6300
45000	39.0600

*Exceeds federal government maximum of
34,000 lbs.

Data taken from Peattie's paper. (3:10)

2.5 SUMMARY AND CONCLUSION

This chapter has given an overview of the basics of road building and the considerations that must be accounted for in highway design, cost assessment and pricing. Roads use up massive amounts of land and materials. There is a great deal of uncertainty in highway design, construction and operation which makes highway engineering and operational policy a dynamic process. Highways have a finite life and they will have to at some point in time be rebuilt. Each user class has its own unique affect on highway design, construction and operational costs.

Conditions for highway construction and operation vary nationwide. Therefore, this thesis recommends that any highway pricing formula be tailored to suit the needs of a specific region.

Fianlly, this chapter has emphasized many times the need for a good maintenance program. A level of service conducive to good highway operations cannot be maintained in the absence of routine maintenance.

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CHAPTER 3

HIGHWAY COST AND USER CHARGES FOR COSTS

3.1 INTRODUCTION

This chapter will highlight the costs of highways, both to build and the costs to users. Table 2.2 showed how differing vehicle weights of the various classes impact road loading and design. There is a need, then, to determine what portion of the marginal costs of a highway is attributable to each user class.

The three categories of highway costs are capital investment costs, operating cost and user costs. Since this thesis deals primarily with highways that are in place, the issue of payment of sunk costs must be dealt with as well as discussing the three categories of costs. The issues just raised of sunk cost, discount rate and inflation will be covered.

The primary sources of federal funds for urban highway projects are the highway trust fund and urban development grants. On the Federal Aid Highway System, the federal government will fund up to 90% of new construction and urban development grants can fully fund a project. Due to the way these revenues are raised by the federal government, it is very likely that some people subsidize highway projects who never benefit from them directly or indirectly. At the same some users who help to generate these revenues, if forced to

pay a toll covering the construction costs, would be paying for the road twice. Still though, the government agencies have to borrow money to build roads or pay for them up front. The highway trust fund is a national asset, and it deserves replenishment when used for highway construction. In turn, the long run benefits of repaying the trust fund through an economic pricing scheme may be a reduction or elimination of the federal taxes used to support the trust fund.

Choosing the appropriate discount rate and inflation rate is a difficult task. Basically, the discount rate should be at least as good as the expected returns on other government investments. It may be just as valid to argue that the government should get a return that would be as good as the best return that could be gained on the same money in the private sector. One possible solution proposed by de Neufville and Stafford is to look at the social discount rate (SDR) which is expressed as;

$$SDR = A(i_g) + \frac{(1 - A)i_g}{1 - t}$$

Where A = Proportion of investment drawn
 from consumers

i_g = Government interest rate

t = Tax rate

They go on to state that the opportunity cost of money to government is on the order of eight to ten percent. (7:170)
Inflation has been added to the cost of 3R work. The

inflation rate should be based on a long term average rather than some optimistic or pessimistic short term rate.

3.2 CAPITAL INVESTMENT COSTS

A strict economist's definition of capital costs are nonhuman resources such as equipment, buildings, inventories and raw materials. In this thesis, capital costs are broadened to include the full investment costs required to produce the full capital plant of a highway and road system. These costs are incurred through preliminary studies, design, right-of-way and land aquisition, and construction.

Preliminary studies are made to determine the feasibility of a proposed project, to look at alternatives and to issue an environmental impact statement. The Federal Aid Highway Act of 1970 requires that guidelines be issued to:

" . . . minimize possible soil erosion from highway construction. . . " and " . . . assure that possible adverse economic, social and environmental affects relating to any proposed project on any Federal Aid system have been fully considered . . . and the cost of eliminating or minimizing such adverse effects and the following:

- 1) air, noise, and water pollution;
- 2) destruction or disruption of man-made and natural resources, aesthetic values, community cohesion and the availability of public facilities and services;
- 3) adverse employment effects, and tax and property value losses;
- 4) injurious displacement of people, business and farms;
- 5) disruption of desirable community and regional growth. (4:18)

These studies are complex, extensive and expensive. In addition, the FHWA has a policy to reimburse land owners for moving and displacement costs.

The relocation costs mentioned above are part of the land aquisition costs for highway development, and payment of these relocation costs are specified by the 1970 Uniform Relocation and Assistance and Land Aquisitions Policies Act. In 1981, nine percent of the total federal expenditures for urban interstate highways was for land aquisition, and 9.4 per cent of the total expenditures for other principal urban arterials was for land. Non federal payments for land for urban interstates was 2.8 per cent and four per cent for land purchases for other principal urban highways. In general land aquisition costs are at least 10 per cent of the total project cost.

When land is purchased for highways, society gives up all benefits of the alternative uses of land in the future, and the opportunity costs are not covered by the initial purchase price. Friedlaender points out that in a world of perfect foresight, the real government purchse price (V) should be; (1:67-68)

$$V = \sum_t^{\infty} \frac{r W_t}{(1 + \pi)^t}$$

Where r = real return on land

W_t = annual social valuation of land

π = social rate of discount

t = year (t)

$r W_t$ = annual income from the land

In this thesis the problem is handled by paying a property and pollution tax to each town or locality the road passes

through. This figure could be a negative value if the benefits of the highway were greater than its costs to a local community.

The most perplexing of capital investment costs are construction costs (includes design costs), maintenance and reconstruction, resurfacing and rehabilitation (3R) costs. The problem with these costs is that it is difficult to determine what proportion of these costs to charge each user class. Obviously, for a highway to carry heavy trucking thicker roadbeds and pavements must be made than that necessary to carry cars. Likewise, indications are that heavy trucking does more damage to roads. The question raised, is what amount of this extra construction cost and road damage should be charged to cars, trucks or tractor trailers.

Chapter Two pointed out that roads fail primarily due to fatigue. To use a mechanical engineering term, roads reach an endurance limit, which means after so many repetitions of loading the system breaks. A combinations of factors cause this, including the aging of materials, such as asphalt drying out and hardening, and the bending action of the pavement. In order to better understand this, an asphaltic concrete pavement design procedure will be presented.

First, the thickness of a full depth asphalt pavement is calculated, and then the trade off of asphalt pavement for base material is figured out based on the actual subgrade conditions. A full depth pavement is one which rests

directly on the subgrade. The first step is to estimate the initial daily traffic number (IDT), or the average number of vehicles expected to use the highway in both directions in the first year. In the absence of data, Tables 3.1 and 3.2 will yield the estimate of truck loads. (5:125-126)

TABLE 3.1 ESTIMATED RANGES IN PER CENT TRUCKS
AND AVERAGE GROSS WEIGHT IN THE U. S.

Type Highway	% Heavy Trucks	Average Gross Weights (KIPS)
City Streets	≤ 5	15-25
Urban Highways		
Primary	5-15	20-30
Interstate	5-10	35-45
Local	≤ 15	15-25

TABLE 3.2 PERCENTAGE OF TOTAL TRUCK TRAFFIC
IN DESIGN LANE

Number of Lanes (Both Directions)	Percentage of Trucks in Design Lane
2	50
4	45 (35-48)
6 Plus	40 (25-48)

Step two: Calculate the daily number of trucks in the design Lane

$$= \text{IDT} \times \frac{\text{Per Cent Heavy Trucks}}{100} \times \frac{\text{Per cent Heavy Trucks in Design Lane}}{100}$$

Step three: Estimate the average gross weight of heavy trucks (Table 3.1) and determine legal single axle load.

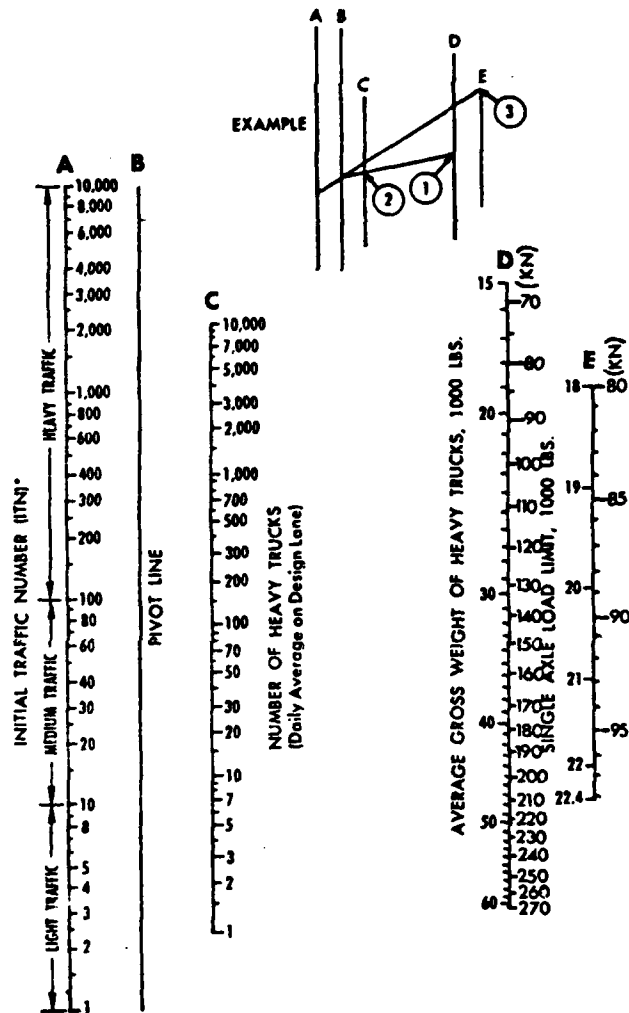


FIG. 3.1 TRAFFIC ANALYSIS CHART (5:127)

Step four: Use nomograph in Figure 3.1 to determine the initial traffic number (ITN).

- A) Enter average gross weight on D and locate the daily average number of heavy trucks in the design lane on C.
- B) Extend the line from points on D and C found in Step A to B and use this as the pivot point.
- C) Locate the single axle load on E and connect a straight line from E through B to read ITN on A.
- D) If $ITN \leq 10$, implying a large number of light trucks and automobiles, then use Figure 3.2 to adjust ITN.

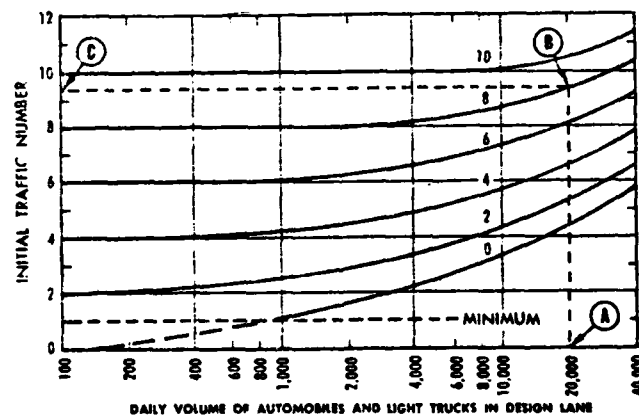


FIG. 3.2 CHART FOR ADJUSTING INITIAL TRAFFIC NUMBER (ITN) FOR DAILY VOLUMES OF AUTOMOBILES AND TRUCKS (5:126)

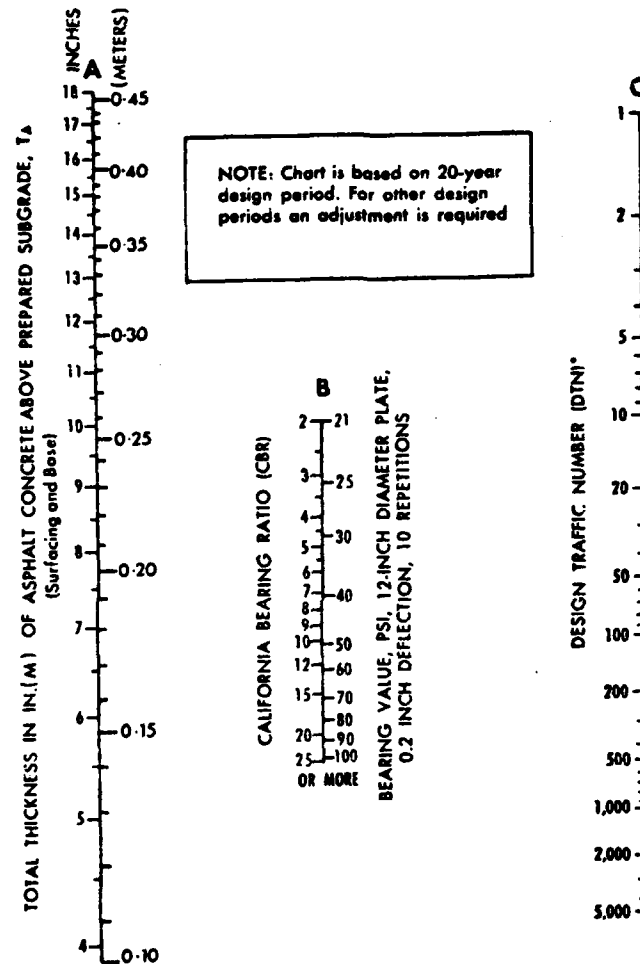


FIG. 3.3 THICKNESS DESIGN CHART FOR ASPHALT PAVEMENT STRUCTURES USING SUBGRADE SOIL CBR OR PLATE-BEARING VALUES (5:131)

Step five: Calculate the design traffic number (DTN).*

A) Assume a design period (n).

B) Estimate the traffic growth rate (r), insuring the rate accounts for truck growth.

C)
$$DTN_{20} = ITN \times \left[\frac{(1 - r)^n - 1}{20 r} \right]^{**}$$

* The DTN is the average daily number of equivalent 18,000 lb axle load applications.

** Thickness design charts based on a period of 20 years.

Step six: From a given strength of the subgrade, as determined by the California Bearing Ratio (CBR) test, use Figure 3.3 to determine the total thickness of asphaltic concrete.

Step seven: Enter Figure 3.4 with DTN and base course conditions to determine asphaltic concrete thickness with a base.

Step eight:
$$\text{Base Thickness} = \text{Total Thickness (Step 6)} - \text{Minimum Thickness (Step 7)}$$

The design method for concrete, while more complex, also relates the total ESALs over the road's life to pavement thickness. As stated in Section 2.4, the demand can be expressed in terms of ESALs. By basing tolls on Esals per vehicle the problem of separating out construction cost among user classes can be solved.

Finally, there are construction costs that have no relation to traffic loads. These basic costs, exclusive of land costs, are subgrade preparation, excavation, drainage, road signs, barriers, markings, etc. These costs should be shared equally by all users.

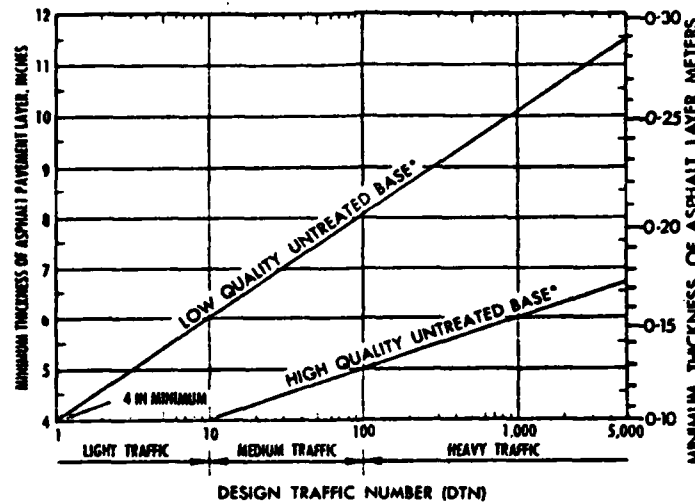


FIG. 3.4 MINIMUM THICKNESS OF ASPHALT PAVEMENT LAYERS OVER UNTREATED GRANULAR BASES (5:135)

Prior to leaving the subject of construction costs some statistics will be given. In 1981 the state capital outlays for construction costs as a per cent of the total budget was 52.4% for urban interstates and 44% for other principal arterials. (3:83). Table 3.3 gives is a breakdown on how this money was spent.

The final area of construction costs are the cost of 3R work that would have to be done even if the design loads were not exceeded (ref. Sec. 2.3). Exceeding the design loads would accelerate the damage and shorten the period between 3R work. The purpose of this work is to keep the road at a given service level in order that the road operation can be carried out as designed.

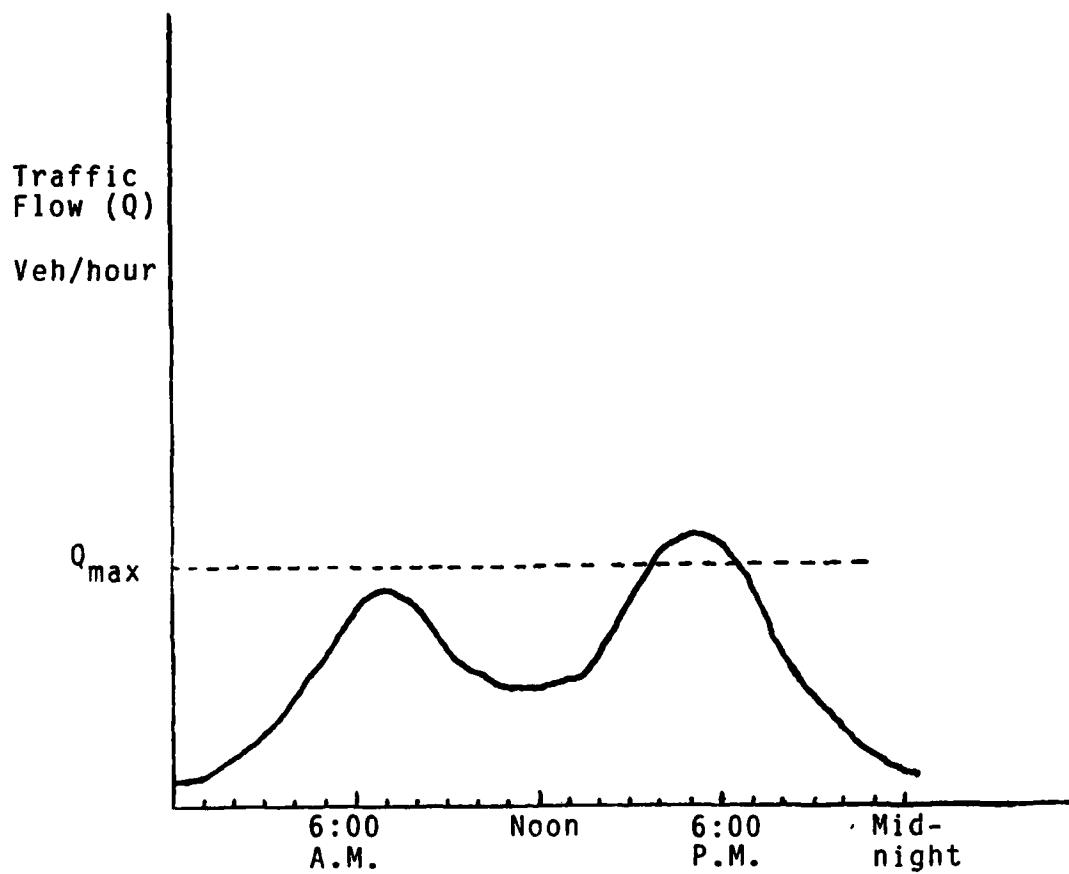


FIG. 3.5 TYPICAL DAILY URBAN
TRAFFIC FLOW

TABLE 3.3 DISTRIBUTION OF CONSTRUCTION COSTS

Item	1979 (%) (2:59)	1981 (%) (3:59)
Equipment, overhead and profit	32.8	35.0
Wages	21.3	19.8
materials	45.9	45/2

3.3 OPERATING COSTS

Operating costs are variable costs that are a function of the road size (w) and traffic density (K). Found on the list of these costs are administrative and toll collection expenses, public safety, energy, routine maintenance and environmental costs. Daily traffic flow in a urban setting will follow a pattern as depicted in Figure 3.5. The cost of toll collection can vary with demand as part time help and split shifts can be used to expand and reduce the labor force, and this is the policy used by the Massachusetts Turnpike Authority. The law enforcement force must remain constant during a shift regardless of demand, because, as officials of the Massachusetts Metropolitan District Council Police and the Massachusetts State Police point out, the highly specialized training of police officers prevents the rapid expansion or reduction of the force. Energy use for highway lights, signs, facility heating and highway vehicles varies with time of day and season of the year rather than traffic loads.

Routine maintenance costs cover the cost of highway painting, vehicular damage to highway property, routine crack repair, pothole repair, grass cutting, drainage system cleaning and repair, litter cleanup and snow removal. Of these costs, crack and pothole repair vary with vehicle loading. The rest of the costs should be charged equally to all users.

The cost of air pollution and noise varies with traffic density because of the numbers of vehicles and due to the fact that as traffic density increases the speed of the traffic is decreased which causes each engine to run longer during each vehicle's journey. Environmental damage from water runoff and scenery defacement are costs that are invariant with demand.

3.4 USER COSTS

User costs fall into two categories, the operating costs to each driver and the cost imposed on each driver by the presence of all the other drivers. The operating costs are the cost of fuel, oil, depreciation, excise taxes on parts and tires and the cost of tolls. The second area of cost is caused by the fact that drivers have a tendency to slow their vehicles in the presence of other vehicles. At the present speed limit of 55 mph this effect is negligible at low traffic densities in freely flowing traffic. As traffic density increases the marginal effects on travel time increases and is substantial at high volume to capacity ratios. Research at the General Motors Research Laboratory on Interstate traffic

in Detroit, Michigan at 3:30-6:30 P.M. with traffic volumes of 1600-2000 vehicles per hour indicated that the average head way between vehicles is about two seconds. (6:4-27) At 55 mph and an average vehicle length of 17 feet this equates to a following distance of 145 feet. An increase in traffic density causes an infringement on this 145 feet of perceived safe space and the tendency is to slow up to maintain a safe distance.

3.5 SUMMARY

This chapter has highlighted the costs that will be considered in the pricing formula developed in the next chapter. In summing up these costs, it must be pointed out that there are certain road costs generated regardless of traffic loads. Secondly, there are costs which are dependent on traffic demand and user category. This is summarized in Table 3.4.

TABLE 3.4 HIGHWAY COST SUMMARY

<u>Cost</u>	<u>Variable With Demand</u>	<u>Variable By User Category</u>
Design	No	Marginally
Pavement	Yes	Yes
Base Course	Yes	Yes
Subgrade	Yes	Yes
Surveying	No	No
Drainage	No	No
Land	No	No

TABLE 3.4 (Cont.)

<u>Cost</u>	<u>Variable with Demand</u>	<u>Variable by User Category</u>
Air Pollution	Yes	Yes
Water Runoff	No	No
Scenery Defacement	No	No
Noise	Yes	Yes
3R	Yes	Yes
Crack and Pothole Repair	Yes	Yes
Snow Removal	No	No
Police	No	No
Toll Collection	Yes	No (unless weighing required)
Road Painting	Yes	No
Accidents	Yes	Uncertain
Drainage Repair	No	No
Energy	No	No
Grass Mowing and Litter Cleanup	No	No
User Energy	Yes	Yes
User Oil	Yes	Yes
User Time Cost	Yes	Yes
Road Damage (user)	Yes	Yes
Vehicle Depreciation	Yes	Yes

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CHAPTER 4

INVESTMENT AND PRICING FORMULAS

4.1 INTRODUCTION

This chapter will lay out the methodology for pricing roads and highways. The analysis begins by looking at the consumer and supplier relationship. By jumping straight into normative economic analysis, one may not fully grasp the essence of marketing road facilities. To begin, it will be assumed that road facilities are provided by privately owned firms responding to a market demand.

4.2 THE ECONOMIC PROCESS

Sensing a demand for road facilities, our hypothetical investor would begin negotiations to either purchase land or lease or buy an easement or right-of-way. The negotiated terms of sale would be the final payment for land. But what about the land's opportunity cost? If the investor is wise, he or she would have looked at all of the investment opportunities available and picked the one most suitable. It will be assumed that, in this case, the best investment would be in roads. Likewise, a land owner given an offer to purchase his or her land would look at the land's alternative economic and personal values and set a selling price.

Next, the investor would set out to build the road

facilities. The construction costs would include all of the costs of preliminary studies, design and construction. Whether the cost is financed with a lump sum payment or through a loan, this investment will still have to be recovered and therefore should be discounted based on the investor's best expected rate of return on alternative investments.

Upon completion, the road would be opened and the owner would raise revenues by toll collection, incurring a cost of collection that varies with demand. Other variable costs include traffic regulation enforcement (police), administration, energy use, maintenance and snow removal. Routine maintenance would include road painting, sign repair, vehicle control facilities repair (guard rails and barriers) and routine repair to road surfaces such as cracks and potholes.

If the owner were running a cars only facility, the same tolls could be charged for each car. If, on the other hand, there were a mix of cars and different classes of trucks, the toll problem would be different. To accomodate trucking, the road would have to be designed for heavier loads; consequently, the automobiles (at design traffic loads) would contribute substantially less to the road's maintenance problems than trucks. If all vehicles are charged the same toll, the more numerous cars would end up subsidizing trucking, and the resulting toll for all vehicles would be greater for several reasons. First, there would be the need to cover the extra construction costs, and when in operation, the added maintenance costs. Finally, a truck takes up more road space,

reduces visibility, which increases the following distance of other vehicles and, for other reasons as well, reduces the total number of vehicles on the road. In order to cover costs with fewer vehicles, the tolls would naturally be higher. As a result of higher tolls, some car users would be priced out of the market, while at the same time, the subsidized truckers may be induced to enter the market.

On the other hand, if the tolls varied by vehicle class and weight, the owner would have to determine first, what portion of the extra cost of construction should be charged to each user, and subsequently, what portion of marginal operating and maintenance costs should be charged to each class of vehicles. For the purpose of this discussion, it will be assumed that the road owner has set the tolls and is able to continue operations.

At the end of the year, the owner applies depreciation to the firm's capital stock, draws up an income statement and prepares a balance sheet. Taxes are then paid on the firm's income and property. As the business continues over the years, the capital plant deteriorates to the point where periodic overhauls of the road are required to keep the road up to a standard that continues to generate a user demand. The routine and periodic maintenance strategies would be business decisions which allowed for the maximization of owner profits, based upon the effects on demand, capital stock depreciation and replacement costs. Eventually the road would wear out and need replacement. Financing of the periodic maintenance and

replacement could be done with a sinking fund or by selling a bond when required. Thus, the basic process by which roads are offered to consumers of transportation has been described in terms of private sector economics.

Anyone in the road business to make a profit would want to collect the highest toll possible from as many vehicles as possible. Therefore, the owner is interested in meeting the demand and keeping traffic flow close to the maximum capacity of the highway. Highway engineers express the last objective as the highway volume to capacity ratio. This thesis will make the assumption that the amount of pleasure driving done on the types of road being dealt with is negligible and that people only use the roads for transportation; that is, to go from one point to another. If a driver were faced with choices of routes to take to a destination, he or she would make the choice that would: a) take the least time b) offer the most comfortable ride c) provide the greatest feeling of safety and d) do the least amount of damage to the vehicle. This creates a conflict with the owner's economic objective of maintaining a high volume to capacity ratio. The decision must be made on how to invest in capital plant. The consumer demand decisions just listed may work interactively or separately. For example, a driver may sacrifice speed to feel safer; or, a road doing the least damage to a car may, at the same time, be providing a comfortable ride, though not always. A road could be smooth, but have narrow lanes and many curves that make the user feel uncomfortable and unsafe. Based upon

this, the road owner is interested in designing a road which would emphasize speed, road quality or high volume to capacity ratios. In engineering terms, this means that the road will vary in width (ω), geometric characteristics (γ) and pavement design (ρ).

This can be viewed as production process where the output or the constructed road is function of ω , γ , and ρ . In equation form, it is expressed as;

$$R = p(\omega, \gamma, \rho) \quad (1)$$

To elaborate further, the road width would include lane widths, medians, shoulders and right-of-way clearance. Road geometry includes the degree of curvature, superelevation, grade, driver line of sight and access and exit features. The pavement design would encompass the load carrying capabilities, type of pavement and all base and subgrade attributes.

There are a multitude of inputs into this production function such as energy, concrete or asphalt, steel, aggregate, labor, etc., but from the owner's point of view the input to process R is the owner's investment (I). At a given level of investment, the owner could produce roads with different characteristics. The owner may be strictly interested in capacity, such as in the case where the demand to fill this capacity is available regardless of the road quality. The road's routing may be such that engineering qualities would be the best way to enhance performance. Finally, the primary customer may be most interested in travel speed, as would be the case for commercial travelers.

Process R can be used to produce a product line that has three sets of characteristics. Set R_1 are roads that emphasize speed by providing direct routing, limited access, multiple lanes and no grade crossings. The second set, R_2 , are roads that utilize highway engineering principals to generate a level of performance. This would include the use of optimal signalization to enhance traffic flow and the construction of over or under passes at key intersections. Other examples are utilizing lead-in spirals and superelevation to improve curve performance, enhanced pavement design to increase road life and the minimization of grade to keep speed constant and to improve driver line of sight. Finally, set R_3 produces roads that emphasize capacity. This characteristic is desirable on urban roads that have to handle rush hour traffic, but need to have a high volume to capacity ratio to prevent underutilization during off peak hours. Figure 1 is a display to the relationships between these sets.

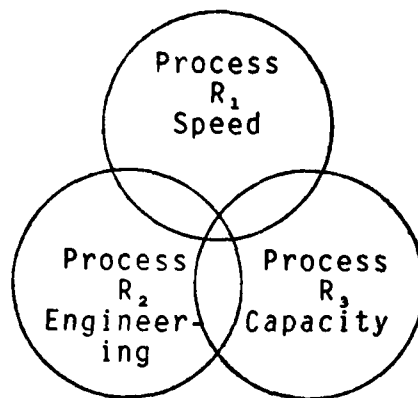


FIG. 4.1 SETS OF ROAD CHARACTERISTICS

The intersection of these three sets is known as the level of service provided by a road. While the traveling public may believe that the best policy is to provide the optimum from each set to each highway project, there are conditions that warrant emphasis of each different sets of construction processes. For example, open areas with long haul traffic are conducive to emphasizing speed. For highways where capacity is the relevant issue, speed can be sacrificed. Parkways and cross town expressways provide a means to move traffic expeditiously throughout the day, but due to land constraints, the engineers design skills are challenged to provide a properly functioning road. This is due to the fact that these roadways are likely to be narrow and have many sharp curves, requiring the ultimate in highway engineering technology to build a road that provides a high capacity at reasonable speed and at the same time allows the drivers to feel confident and safe during their travel on such highways. The same would be true of major arteries with a large number of grade intersections. The design of these intersections and the method of signalization is critical to optimizing performance.

Regardless of the initial level of investment or construction process chosen, the operational policy of a highway plays a major role in the performance of any highway. Operational policy is centered around the operating agency's maintenance program and traffic control procedures. The maintenance investments should be included in the overall

investment, and traffic control (CT) is the second input into the highway production process.

4.3 DETERMINATION OF TRAFFIC VOLUME

It is important to understand the relationship between traffic density (K) in terms of cars per mile, vehicle speed (V) expressed as miles per hour and lane traffic flow (Q) which has units of vehicles per hour. The total flow for all lanes in one direction is the traffic volume, and the maximum total flow is the highway's capacity. The pricing formula developed in this chapter uses the flow as the expression for demand in a period. However, the measurement of traffic flow is not easy to do in the field, but velocity can be measured easily with radar. The flow can then be analytically derived from the measured mean traffic speed.

The expressions developed here are for free stream traffic flow and will not work for highways or roads where stop signs or traffic signals are prevalent. The problem of weaving traffic at access points and exits is handled by designing the on and off ramps so that they do not interfere with the free stream traffic flow. This assumption does not work at high traffic densities, because the weaving traffic causes other traffic to brake or even stop, sending shock waves through the traffic flow for over a mile from the source.

Several models for free stream traffic flow have been proposed, all of which give reasonable answers, but each seem to be tailored to a certain type of highway. One of

the first models to relate traffic speed and density was proposed by Greenshields which states; (3:49)

$$V = V_f - \frac{K}{K_j} V_f \quad (2)$$

Where V_f = free flow speed
 K_j = Jam density (density where V and Q approach zero)

Further, observations show that freestream traffic flow is related to velocity and density by the expression;

$$Q = KV \quad (3)$$

Substituting into Equation 2 yields;

$$Q = VK_j - \frac{K_j}{V_f} V^2 \quad (4)$$

Other models have been proposed and will be summarized. Greenberg's model is stated as;

$$V = V_m \ln\left(\frac{K_j}{V_f}\right) \quad (5)$$

Where V_m = Maximum speed

has shown good correlation to field data, but is invalid as K approaches zero. (3:49)

Underwoods model dealing with flow at low density is expressed as follows; (3:49)

$$V = V_f e^{-K/K_m}$$

Where K_m = concentration at maximum flow (6)

Finally, Dick's study of urban traffic showed that there is an upper limit to speed, and this assumption was combined

with Greenberg's model to yield a graph of the speed plotted against density as shown in Figure 4.2.

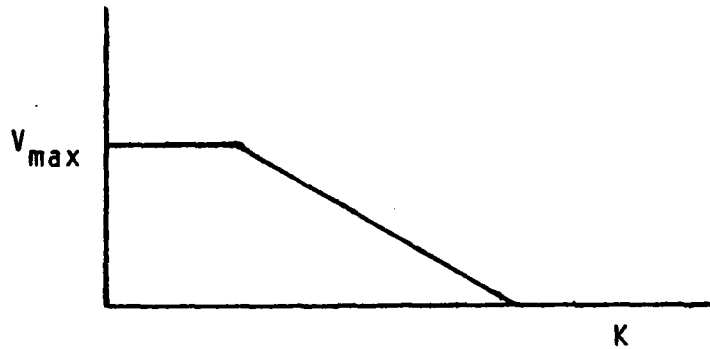


FIG 4.2 DICK'S SPEED/DENSITY RELATIONSHIP (3:53-56)

The problem of highway bottlenecks have also been analyzed. Given a highway capacity Q and the bottleneck capacity Q_B , a queue will form if Q exceeds Q_B and "a wave of increasing density is transmitted rearward with a speed $\Delta Q/\Delta K$." (3:60)

It is difficult to measure actual performance and extrapolate meaningful data, due to the fact that density must be measured over an appropriate distance. Density is measured by vehicle headway, which is the time difference between one vehicle's front bumper passing a point and the following vehicle's front bumper passing the same point. If the vehicles' speed and average length are known, the distance between the vehicles can be calculated. In the past, headway was measured at a specific point, whereas the behavior over a distance of a mile, for example, is a better indicator of true traffic density. Studies using

aerial photography have been used to overcome this problem. The results of these studies have shown that driver behavior is varied, and that the following distance fits a normal distribution. Some drivers follow very closely, while others have a large headway. In addition, these same studies have shown that this behavior varies by lane as well. (6:11-21) Studies by the General Motors Research Laboratory have shown that this behavior varies by vehicle size as well. (5:4-27)

Because of these complexities in measuring traffic density and flow, the analytic models developed to date form a basis for any road operator to estimate a highway's flow. Observed data on traffic velocity and flow have yielded results that a quadratic equation of the form;

$$Q = aV^2 + bV + c \quad (7)$$

would produce a curve fitting the data well. This result has been verified by studies done by Walters in 1962 (1) and Keeler and Small. (7) To close this discussion, some general figures for capacity of various roadways will be given. Freeways have a capacity of 2000 cars per hour per lane and streets with signalized intersections have a capacity of 1700 cars per lane per hour of green light. (2:252-269)

4.4 SOCIAL PROBLEM FORMULATION

Urban highways, roads and streets all fall under the public domain. Without an extensive system of public roads members of society would be territorily trapped. Other social benefits accrue from public safety factors such as police protection, fire safety and medical services. Finally,

without the public's right to eminent domain the land acquisition required to make an efficient road system would be virtually impossible. While the description of the road building and operating process can be described in terms of the private market as was done in Section 4.2 in order to understand the basic elements of providing highways, there are certain characteristics of public ownership that make social economics the appropriate means to set pricing.

Roads are a public good since the consumption of transportation services by one user does not prevent the consumption of the same services by other users. As this thesis has pointed out, there are costs imposed by each user on the system. In addition, the existence of certain types of road systems imposes costs to property owners bordering on these systems. The objective of this thesis is to develop a pricing formula that optimizes investments, accounts for all costs and maximizes net social benefits.

Theoretically, the decision to travel on a given road depends on how each driver perceives the benefits and costs of using the system. Referring to Figure 4.3, at a given cost there will be a certain number of users who feel that the benefits of making the trip are greater than the costs of making the trip. As has been shown (Ref. Ch. 3), as the number of users increases, the marginal costs imposed on the system and the other users increases. In the absence of pricing to account for these additional costs, users will continue to enter the system until the average user cost

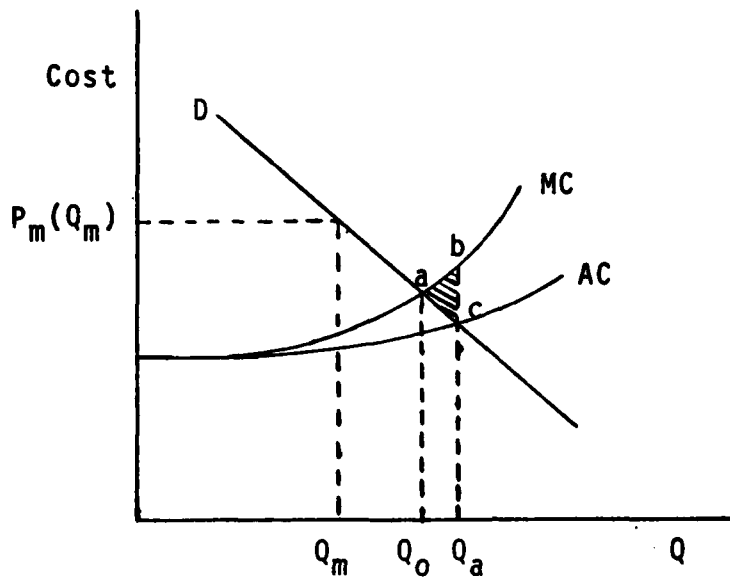


FIG 4.3 HIGHWAY DEMAND AND COSTS

curve intersects the demand curve. At the demand beyond Q_o the benefits to the users is the area Q_oacQ_a . The loss, area abc , which is depicted as the shaded area, is the dead weight loss and is the payment above average costs required to account for the true social costs to all other motorists in the system. (5:92-92)

Highways have a heterogeneous mix of traffic that varies by vehicle type, weight, use and driver income. All of these variables affect either costs or the drivers perception of benefits. The demand at any time period is a sum of all of the vehicles in all of the user classes. If u equals

the number of users in a class i , the demand (Q) in terms of traffic flow in a period (τ) is;

$$Q_{\tau} = \sum_i u_i \quad (7)$$

Assuming that the appropriate tolls could be charged to the users, this toll would be a function of the demand and is expressed as $P(Q_{\tau})$.

To begin the pricing formulation, the following parameters are defined.

ω = road width

γ = road geometric characteristics

ρ = pavement and roadbed characteristics

ϵ = any other engineering improvements

ℓ = traffic loading

Q_{τ} = demand in period

$P_{\tau}(Q_{\tau})$ = price as a function of Q charged in period τ

τ = A given period of loading. The year is divided into T total periods.

Since an explicit expression for the price of highway use is desired, a separate variable cost function (C_{τ}) is defined that includes the drivers' time costs, vehicle operating costs, law enforcement costs, toll collection and energy. This function varies according to the values of ω , γ , ρ , ϵ , ℓ , and Q_{τ} . Assuming there are m vehicles on the road (Fig. 4.3) in a given period, the total benefits to all drivers is the benefits derived by the m th driver plus

any consumer surplus. This is expressed in Equation 8 as;

$$\text{Benefits} = \int_0^{Q_m} P_m(Q_m) dQ \quad (8)$$

The costs associated with highways that are charged as an annual rent are construction costs, maintenance costs and land costs. Construction costs include the cost of preliminary studies, design, construction and all associated costs of changes and delays. They are amortized over the projected life of the road (n years), using the capital recovery factor (crf) where i is the discount rate and;

$$\text{crf} = \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right]$$

and g_i is a function relating parameters to cost. The annual construction costs (A_1) are a function of ω , γ , ρ , which includes the cost for design loads, and ϵ . They are expressed as, $A_1(\omega, \gamma, \rho, \epsilon) = \text{crf } g_1(\omega, \gamma, \rho, \epsilon)$.

3R work will be scheduled every m years. This cost, designated A_2 , is a function of ω , ρ and λ . Since this is part of the capital investment costs of the road, it will be paid for by current users as retained earnings. Taking the current estimate of 3R work and adjusting for inflation (r), this cost is amortized based on the sinking fund factor (sff) which is;

$$\text{sff} = \left[\frac{i}{(1+i)^m - 1} \right]$$

3R costs are written as $A_2(\omega, \rho, \ell) = \text{sff}(1 + r)^m g_2(\omega, \rho, \ell)$.

Routine maintenance costs are paid for annually. These costs are a function of ω , ρ and ℓ . The expression for these costs is $A_3(\omega, \rho, \ell)$.

Finally, land costs are comprised of the original land purchase price plus an annual rent. This annual rent, which includes the opportunity and social costs may be viewed as an annual property tax. Land purchase costs would be amortized over the initial road life using the crf and are a function of the road width. This cost is designated $A_4(\omega)$. The land rent is a function of the road width and the demand. This annual rent is $A_5(\omega, Q_\tau)$. This annual rent could be a negative value or a benefit if in fact the road proved to benefit the landowners or locality bordering the road.

Summarizing;

- 1) $P_\tau(Q_\tau)$ = price to user in a given period, τ , as a function of demand.
- 2) $C_\tau(Q_\tau, \omega, \gamma, \rho, \epsilon, \ell)$ = variable cost to sys- in period τ .
- 3) $A_1(\omega, \gamma, \rho, \epsilon)$ = construction costs
- 4) $A_2(\omega, \rho, \ell)$ = periodic 3R work costs.
- 5) $A_3(\omega, \rho, \ell)$ = routine maintenance costs.
- 6) $A_4(\omega)$ = land aquisition costs.
- 7) $A_5(\omega, Q_\tau)$ = annual property and pollution tax.

Finally, the complete expression for net benefits of a given road or highway annually is;

$$NB = \sum_{\tau=1}^T \left[\int_0^{Q_\tau} P_\tau(Q_\tau) dQ_\tau - Q_\tau (C_\tau(Q_\tau, \omega, \gamma, \rho, \epsilon, \ell)) \right] - \left[A_1(\omega, \gamma, \rho, \epsilon) + A_2(\omega, \rho, \ell) + A_3(\omega, \rho, \ell) + A_4(\omega) + A_5(\omega, Q_\tau) \right] \quad (9)$$

Assuming the second order conditions are met, maximization with respect to each parameter yields the following. First, differentiating with respect to Q_τ and setting the expression equal to zero yields;

$$0 = \sum_{\tau=1}^T \left[P_\tau - Q_\tau \frac{\partial C_\tau}{\partial Q_\tau} \right] - \frac{\partial A_s}{\partial Q_\tau}$$

$$P_\tau = Q_\tau \frac{\partial C_\tau}{\partial Q_\tau} + \frac{\partial A_s}{\partial Q_\tau} \quad \tau = 1, \dots, T \quad (10)$$

Equation 10 shows that the short run price must equal the short run marginal costs, which includes the short run marginal social costs as well.

Differentiating with respect to ω , and setting this expression equal to zero yields the following.

$$0 = \sum_{\tau=1}^T -Q_\tau \frac{\partial C_\tau}{\partial \omega} - \left[\frac{\partial A_1}{\partial \omega} + \frac{\partial A_2}{\partial \omega} + \frac{\partial A_3}{\partial \omega} + \frac{\partial A_4}{\partial \omega} + \frac{\partial A_5}{\partial \omega} \right]$$

$$-\sum_{\tau=1}^T Q_\tau \frac{\partial C_\tau}{\partial \omega} = \frac{\partial A_1}{\partial \omega} + \frac{\partial A_2}{\partial \omega} + \frac{\partial A_3}{\partial \omega} + \frac{\partial A_4}{\partial \omega} + \frac{\partial A_5}{\partial \omega} \quad (11)$$

The left hand side of Equation 11 is a negative user cost or savings, and the entire equation says that investments in road expansion should be held to the number of lanes where the marginal savings of the extra lane equals the sum of the marginal costs of providing the extra highway width. The maximization expressions for partial differentiation with respect to ρ , γ and ϵ are shown in Equations 12 through 14. Equation 12 states that the investment

$$-\sum_{\tau=1}^T Q_{\tau} \frac{\partial C_{\tau}}{\partial \rho} = \frac{\partial A_1}{\partial \rho} + \frac{\partial A_2}{\partial \rho} + \frac{\partial A_3}{\partial \rho} \quad (12)$$

$$-\sum_{\tau=1}^T Q_{\tau} \frac{\partial C_{\tau}}{\partial \gamma} = \frac{\partial A_1}{\partial \gamma} \quad (13)$$

$$-\sum_{\tau=1}^T Q_{\tau} \frac{\partial C_{\tau}}{\partial \epsilon} = \frac{\partial A_1}{\partial \epsilon} \quad (14)$$

in pavement design should be at the level where the marginal savings to users equals the marginal costs of this level of investment in the initial construction plus the marginal costs of this investment to achieve a level of annual maintenance and projected 3R work. Here it is worthwhile to note that the annual maintenance costs and periodic 3R work costs are based on estimated projections. The subject of uncertainty and its affect on actual performance has been discussed. While the true costs of maintenance and rehabilitation cannot be accurately forecasted, it is still important to insure that the users pay for these inevitable costs. It is imperative that operational policy be developed to insure that the actual costs of the highway's maintenance and rehabilitation program be kept as close as possible to the projected values. This is the only way that public highway agencies can expect any highway to perform as designed. In a similar fashion, Equations 13 and 14 state that the the marginal costs of the investments in highway geometric and engineering qualities be equal to the marginal savings projected for the users.

Finally, differentiating with respect to ℓ and setting this equal to zero yields, with algebraic manipulation;

$$-\sum_{\tau=1}^T Q_{\tau} \frac{\partial C_{\tau}}{\partial \ell} = \frac{\partial A_2}{\partial \ell} + \frac{\partial A_3}{\partial \ell} \quad (15)$$

Equation 15 has implications for operational policy in that it states that the level of traffic loads must be kept at the point where the marginal costs of routine maintenance and 3R work equals the marginal savings to the users. In other words, load regulations must be enforced if the highway is to perform as designed.

In a first best world there are three rules that provide economic efficiency. Rule one states that the rate of technical substitution (RTS) for any set of inputs be the same for the production of each output. To reiterate, it was proposed (Sec. 4.2) that there are three processes that can be used to provide highways with various performance characteristics. Process R_1 will be used to explain the derivation of the RTS for this process. Figure 4.4 is a hypothetical depiction of this process, showing that an increase in traffic control allows for a decrease in investment up to a point.

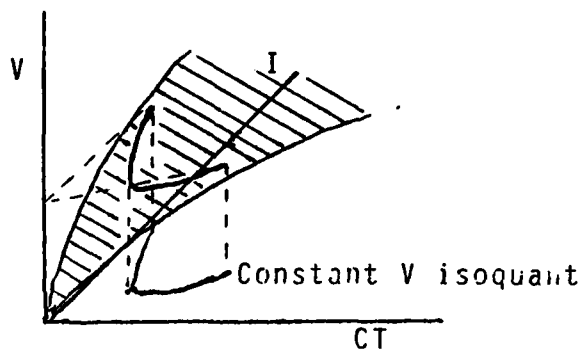


FIG. 4.4 THREE DIMENSIONAL REPRESENTATION OF PROCESS R_1

The following is a derivation of the RTS for R_1 .

$$R_1 = f(I, CT)$$

$$dR_1 = \frac{\partial f}{\partial I} \cdot \Delta I + \frac{\partial f}{\partial CT} \cdot \Delta CT$$

Since dR_1 on an isoquant (constant level of output) is zero;

$$0 = \frac{\partial f}{\partial I} \cdot \Delta I + \frac{\partial f}{\partial CT} \cdot \Delta CT$$

$$\frac{\frac{\partial f}{\partial I}}{\frac{\partial f}{\partial CT}} = - \frac{\Delta CT}{\Delta I} \quad (16)$$

The left hand side of Equation 16 is the ratio of marginal products of I and CT , and the right hand side of the equation is defined as the rate of technical substitution. The generation of capacity and engineering quality through processes R_1 and R_2 follows the same logic. Then for rule one to hold, the following must be true.

$$RTS (R_1) = RTS (R_2) = RTS (R_3) \quad (17)$$

or

$$\left[\frac{MP_I}{MP_{CT}} \right]_{R_1} = \left[\frac{MP_I}{MP_{CT}} \right]_{R_2} = \left[\frac{MP_I}{MP_{CT}} \right]_{R_3} \quad (18)$$

Equations 11 through 15 will insure that the appropriate investment decisions are made for a particular road, and that the requirements of Equations 17 and 18 are met.

To fulfill the next two efficiency rules, some assumptions will be made about an urban road system. The knowledgeable driver will have several choices of routes between destinations within an urban area. It is further assumed that the driver will have enough information to make a choice of routes based on the cost of using each of the alternatives. This information would be derived from experience, radio reports and from seeing the level of congestion on a particular route. The routes can be divided into categories which are similar in characteristics to the FHWA functional groupings of urban highways and streets. The FHWA has classified these roadways as primary arterials, secondary arterials and collectors. (9: II 14-II 15) Close inspection of an urban highway system will likely show that there will be at least one or more of these groups of roads between the primary areas of travel concentration. These groupings of roads will be divided into three categories. The first category (C1) is comprised of the primary arterials that have multilanes of traffic in both directions and completely controlled access. Category two (C2) highways are secondary arterials that have limited access and includes major state highways and parkways. Category three (C3) roads are collectors and major city thoroughfares. It will be assumed that other city streets do not offer competitive modes of transportation. In order to maximize the utilization of the entire system, the second and third rules of economic efficiency have to be met.

Rule two states that the marginal product of investment and traffic control be the same for all categories of roads. That is;

$$MP_I(C1) = MP_I(C2) = MP_I(C3) \quad (19a)$$

$$MP_{CT}(C1) = MP_{CT}(C2) = MP_{CT}(C3) \quad (19b)$$

If the stated assumptions hold and the pricing formulas are implemented, then the conditions in Equations 19a and 19b can be expected to be met.

Given an investment budget and the maximum utilization of traffic control procedures, the production frontiers in terms of service levels for each category of highway can be determined. The third rule for economic efficiency states that the rate of product transformation (RPT) for each category must be equal. This says that given a production frontier curve for each highway category, the investments in dollars and in traffic control should be made at the level for each where the slopes of all three curves (three categories) is equal. In equation form this is;

$$RPT(C1) = RPT(C2) = RPT(C3) \quad (20)$$

Again, the optimization of performance based on the expected demand and the investment decisions derived in Equations 11 through 15 should meet this requirement.

The last issue is how to predict if the tolls raised by Equation 10 will cover the cost of the road. As long as $MC < AC$, the revenues raised will not cover costs. Keeler and Small in their study on user charges assert that setting the price equal to marginal costs will yield a surplus if

there are returns to scale in highway construction, break even if there are constant returns to scale and require a subsidy if there are decreasing returns to scale. (7:4) Since this thesis asserts that there are multiple input process and deals with an entire urban system the problem of determining the returns to scale is complex.

Work done by Bailey and Friedlaender presents a means of evaluating the returns to scale in a multiproduct environment. First the outputs from the three production process R_1 , R_2 and R_3 are, for a set level, V_i , EQ_j , and Q_k respectively. The economies of scope (S_c) is defined as;

$$S_c = \frac{[C(V_i, 0, 0) + C(0, EQ_j, 0) + C(0, 0, Q_k)]}{C(V_i, EQ_j, Q_k)} \quad (21)$$

The function C defines the cost of producing the three products listed in parenthesis, with a zero meaning that the particular product has been omitted. The product specific economies of scale is defined in the following three equations.

$$S_{V_i} = \frac{C(V_i, EQ_j, Q_k) - C(0, EQ_j, Q_k)}{V_i} \quad (22a)$$

$$S_{EQ_j} = \frac{C(V_i, EQ_j, Q_k) - C(V_i, 0, Q_k)}{EQ_j} \quad (22b)$$

$$S_{Q_k} = \frac{C(V_i, EQ_j, Q_k) - C(V_i, EQ_j, 0)}{Q_k} \quad (22c)$$

Also, define w by the following equations.

$$w_V = \frac{Q_{Vi}(P_\tau(Q_{Vi}))}{Q_{Vi}(P_\tau(Q_{Vi})) + Q_{EQj}(P_\tau(Q_{EQj})) + Q_{Qk}(P_\tau(Q_{Qk}))} \quad (23a)$$

$$w_{EQ} = \frac{Q_{EQj}(P_\tau(Q_{EQj}))}{Q_{Vi}(P_\tau(Q_{Vi})) + Q_{EQj}(P_\tau(Q_{EQj})) + Q_{Qk}(P_\tau(Q_{Qk}))} \quad (23b)$$

$$w_Q = \frac{Q_{Qk}(P_\tau(Q_{Qk}))}{Q_{Vi}(P_\tau(Q_{Vi})) + Q_{EQj}(P_\tau(Q_{EQj})) + Q_{Qk}(P_\tau(Q_{Qk}))} \quad (23c)$$

$$\tau = 1, \dots, T$$

Q_{Vi} is the traffic flow generated in a given period by speed V_i , Q_{EQj} is the flow generated by engineering qualities at level EQj and Q_{Qk} is the flow generated by the capacity k . Combining equations 22 and 23, the overall scale economies is expressed as;

$$S = \frac{w_V S_V + w_{EQ} S_{EQ} + w_Q S_Q}{(1 - S_c)} \quad (24)$$

While investing in just one of the three outputs may not show decreasing economies of scale, all three combined in an urban system may produce economies of scale. Economies of scale mean the isoquants in the production function are closely space, meaning that a small change in inputs will result in a greater change in the highway's level of service. This means that the urban highway system will handle higher volumes of traffic with decreasing levels of investment in construction and traffic controls. However, by the very

nature of costs the increasing numbers of drivers inflicts on the system, the marginal costs will be rising as the average costs falls. Thus the returns to scale would predict if the revenues raised will cover highway costs.

4.5 SUMMARY

The chapter began by using a hypothetical example of road building and operation to explain the process involved in providing highway transportation. The example concluded by pointing out that if highways were provided in the private sector, that all of the costs of producing and operating the highways would have to be paid for by the consumers of highway transportation, or the system could not function. The same is true for highways under public ownership.

Since the pricing formula developed in this chapter measured highway demand in terms of traffic flow, the means by which to analytically determine the flow at any time was presented. The average traffic speed is easily measured, but the other variables, density and flow, are not. Thus the requirement for an analytic method to derive these two quantities from the traffic speed.

Finally, the highway pricing formula was developed around the well established theories of optimal highway demand and pricing. The pricing formula also established the long run investment criteria for highway projects.

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CHAPTER 5

EXAMPLE OF PROCEDURES FOR APPLYING MODEL

5.1 PROBLEM DESCRIPTION

Currently, Boston, Massachusetts has a major problem with congestion on the central north-south artery through the city's core. This artery is comprised of Massachusetts Rt. 3 and Interstate 93, and both form a common route from the town of Braintree in the South to Storrow Drive on the northern edge of Boston. The central artery junctions two major arterials, U. S. Rt. 1 and Mass. Rt. 1A, in the city's core.

Congestion becomes acute during the morning and evening rush hours. During the summer months traffic to and from the South Shore causes high levels of congestion as well, and is particularly bad on Sunday evenings and Monday mornings.

Perhaps the most significant factor in the congestion at high volume to capacity ratios is the fact that the central artery can quickly become a badly behaved (unstable) queuing system if a breakdown closes one lane, which is equivalent in queuing theory terms to eliminating one server. A breakdown at rush hour slows the flow to stop and go traffic.

To solve the problem the Massachusetts Department of Public Works has proposed a central artery improvement program and Interstate 90 extension into a third harbor tunnel.

The purpose of the project is to improve the traffic flow on the central artery and other highway facilities connecting to it. Proposed improvements include widening and depressing the central artery, improving ramp connections and eliminating the elevated portion of I-93. Without such improvements, it is felt that congestion problems will worsen and severely affect the operation of the core's highway system and the business functions of the core itself.

The project intends to put the portion of I-93 from Albany St. in South Bay to the Rt. 1 interchange underground and widen the highway from the current three lanes of traffic in both directions to four or five lanes in both directions. In addition I-90 will be extended via tunnel across the Boston inner harbor to connect to Rt. 1A. The cost of various alternatives ranges from 1.895 billion dollars to 2.187 billion dollars. The project, exclusive of the tunnel, is expected to cost \$1.314 billion. Rehabilitation of the existing system would cost \$33 million. (5:iv-vi)

5.2 TRAFFIC FLOW

There are many alternative routes that could be used to improve traffic flow into and through the Boston Core. One advantage of making overall systems improvements is that the current traffic flow can be spread around, offering relief to the central artery exits. Figure 5.1 is a map of the area and Table 5.1 lists the alternative routes that can be used to move the north-south traffic along this corridor.

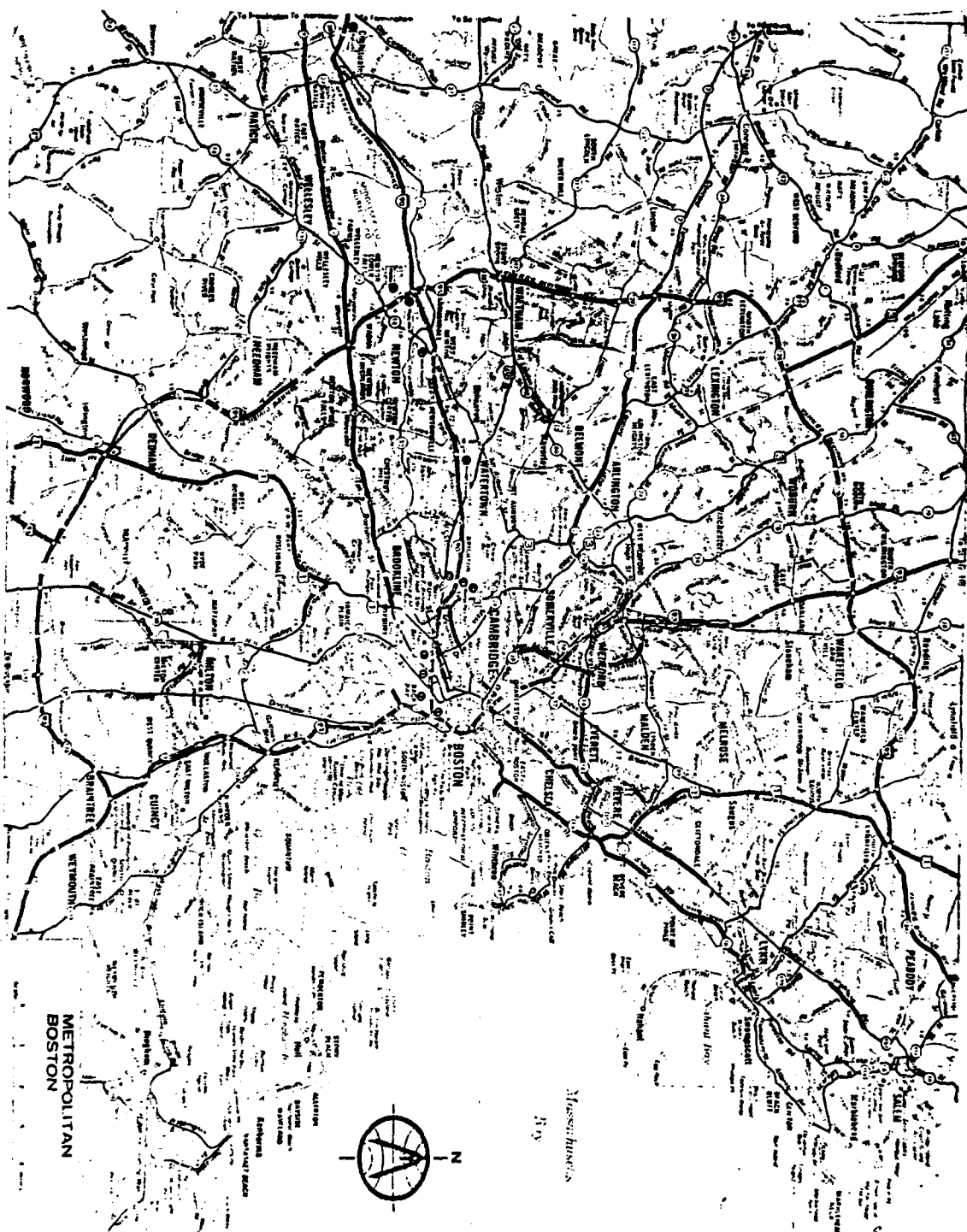


FIG. 5.1

TABLE 5.1
ALTERNATIVE ROUTES OF TRAVEL

Rt.#	Route Designation	Category	Direction	Zones
1	1A	C2	South	34,33,32 31,14,13
2	107-16-1A	C3-C2	"	"
3	107-16-1	C3-C2-C1	"	"
4	107-16-99	C3-C2-C3	"	"
5	128-1	C2-C1	"	35,30,29 16,15
6	1S	"	"	"
7	1-16-99	C2	"	"
8	1-99	C2	"	"
9	Main St.- 99	C3-C2	"	"
10	I-93	C1	North/ South	"
11	128-193	C1	South	"
12	38-28	C3-C2	"	"
13	28	C2	"	"
14	3-16-38	C3	"	"
15	16-28	C2	"	"
16	53-3A-Wm- Morrissey	C3-C2	North	9,21,22, 40,41
17	3-193	C1	"	"
18	28-Dor- chester Ave.	C3	"	"

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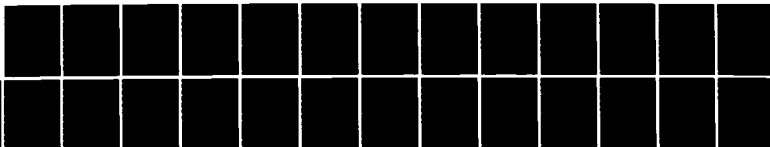
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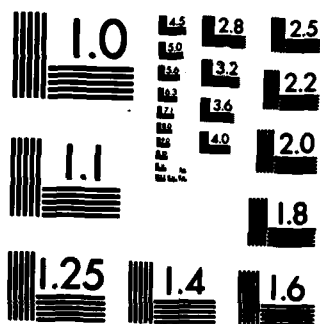
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 5.1 (Cont.)

Rt.#	Route Designation	Category	Direction	Zones
19	28	C3-C2-C3	North	9,21,22, 40,41
20	138-28	C3-C2	"	"
21	1-Wash- ington St.	C3	"	8,23,24, 39
22	1	C2-C3	"	"
23	114-128	C2-C1	West	32,31
24	129-128	C3-C1	"	31
25	60	C3	"	14,16
26	16	C2	"	14,15,16
27	16-99	C2	"	15,16

In order to understand this route selection, a general description of the Boston area traffic flow must be given. Referring to Figure 5.1, it is clear that the main traffic arteries form a radial pattern around the city's central core. In 1977 the Executive Office of Transportation and Construction for the Commonwealth of Massachusetts did a regional study on the area's trip patterns. As a result, it was shown that the regional traffic flow followed six distinct corridors. Further, each corridor was divided into zones of trip origination (Fig. 5.2). The central artery is fed by traffic from the North Shore corridor, the North corridor, the Southwest corridor and the South Shore corridor. It will be assumed that the traffic flow on the central

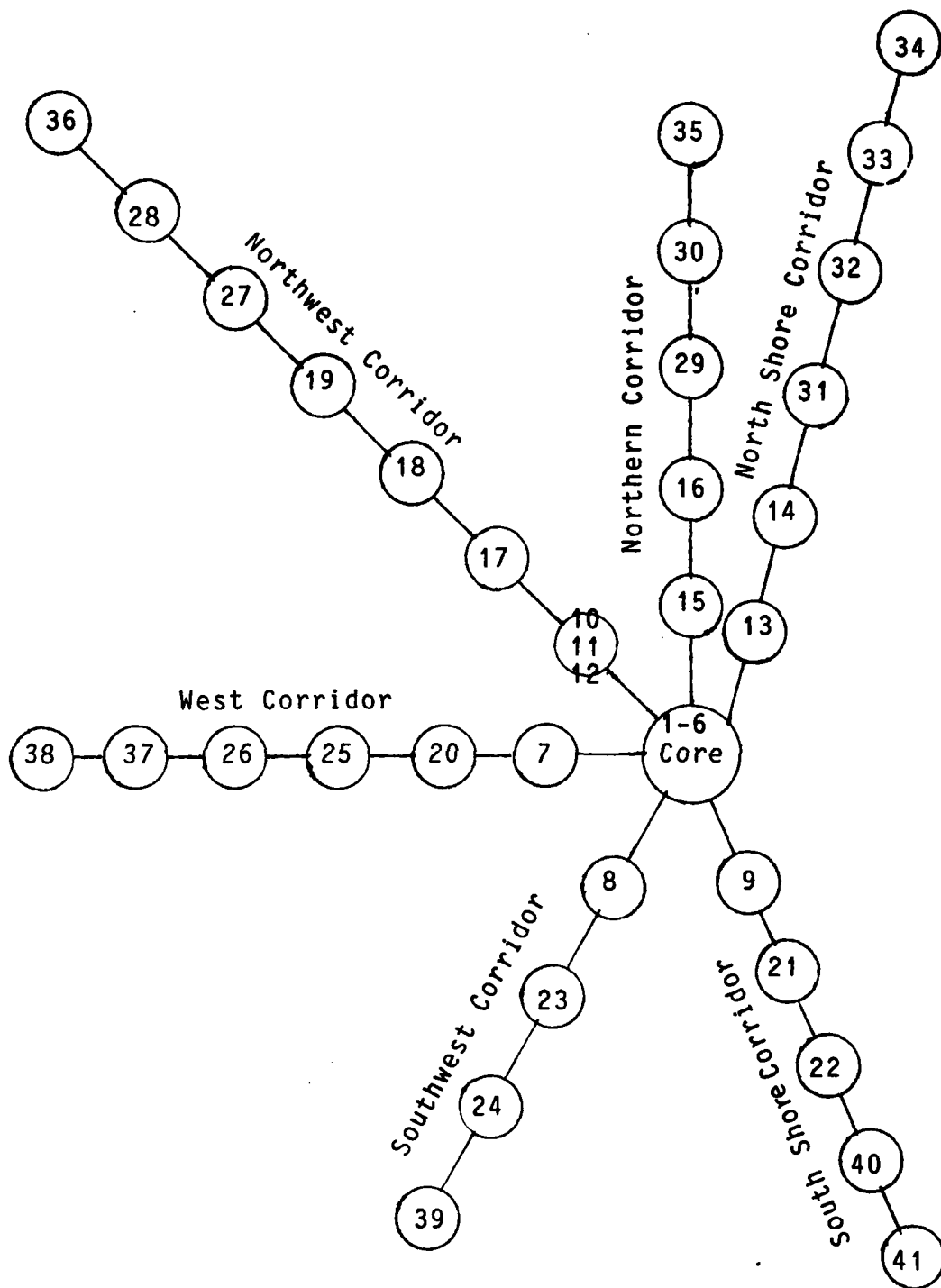


FIG. 5.2 BOSTON TRAVEL CORRIDORS AND
ZONES OF TRIP ORIGINS

artery is independent of the influences of the Western and Northwestern corridors. From this assumption, the route structure given in Table 5.1 can be laid out as shown in Figure 5.3.

The next step is to assign probable traffic flows on the routes. The estimated 1980 number of trips from each zone is shown on Figures 5.4 through 5.7. This data was taken from the Program for Mass Transportation study done by the Executive Office of Transportation and Construction.

The southbound traffic summary from the North Shore Corridor shows that Rt. 128 will have at least 11,200 trips in the A.M. period from circumferential traffic and would share 11,660 trips with Rts. 107 and 1A to Zone 32. The total lane capacity of Rt. 128 is 6000 vehicles per hour (vph) and the other routes at optimal flow could be expected to have an hourly capacity of 4500 vph. This is based on the signals on the C2 and C3 routes having green lights 40 minutes out of every hour. It also assumes that C1 routes have a lane capacity of 2000 vph and C2 and C3 routes with grade crossings have a capacity of 1700 vph per hour of green light. From Zone 32 to Zone 14, Rts. 1, 1A and 107 would share 11,410 trips (capacity - 6800 vph). From Zone 14 inbound Rts. 1, and 1A would share 13,880 with a capacity of 8000 vph.

From the North Corridor, I-93 and Rt. 28 would share 26,660 trips plus that portion of the 11,200 trips from Rt. 128 that use I-93 southbound and approximately 4,000

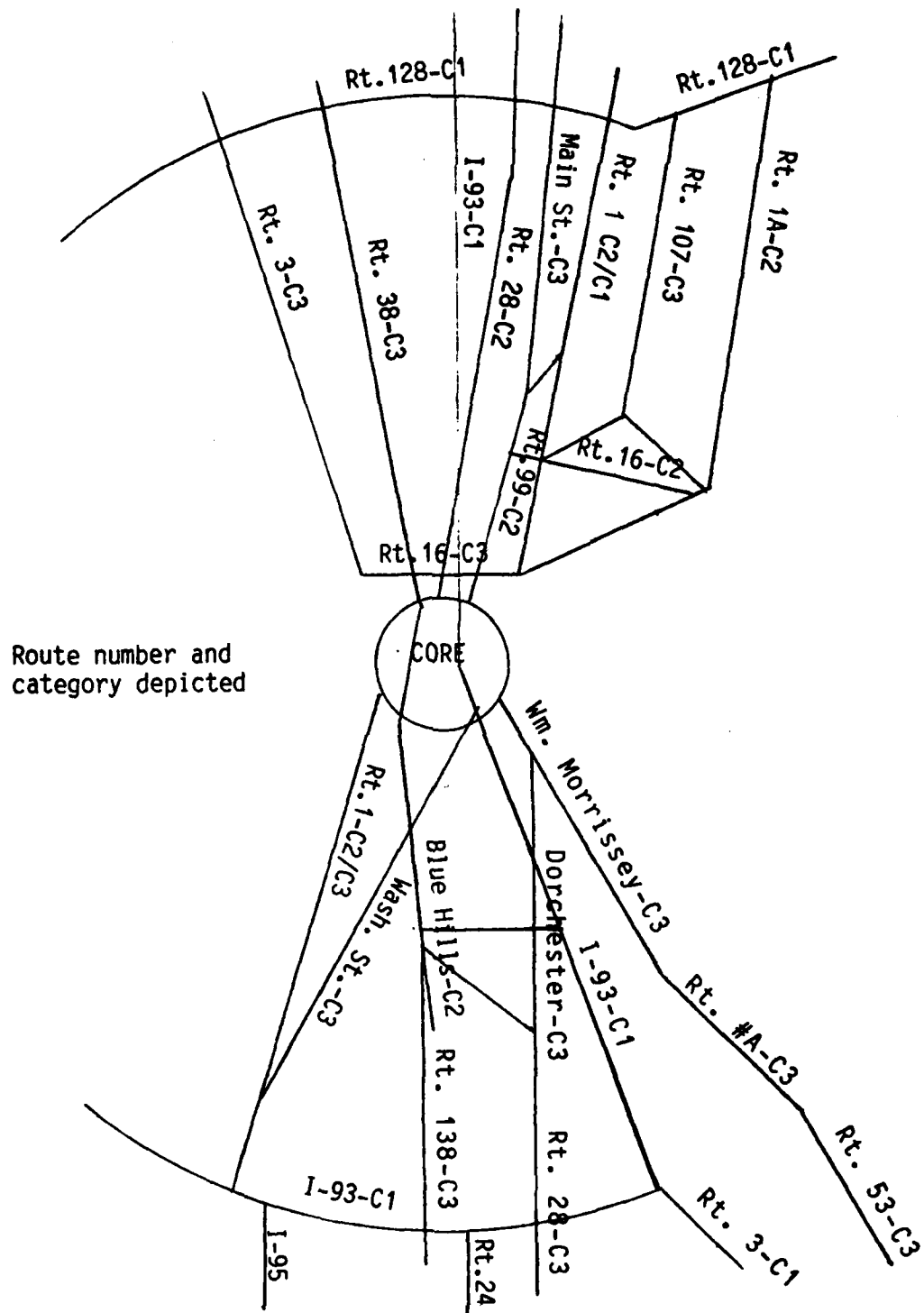




FIG. 5.3 NORTH-SOUTH CORRIDOR ROUTE STRUCTURE



	<u>Cities</u>	<u>Direction</u>	<u>Cum. Trips</u>	<u>Likely Routes</u>
34	Beverly	Inward	3500	1,5,2-4
	Hamilton			
	Manchester	Core	2400	5,11
	Topsfield			
	Wenham	Through	300	1,2-5,11
		Circumfer- ential	300	11
33	Danvers	Inward	4400	1,2-5
	Middleton			
	Peabody	Core	4560	1,2-5,11
	Salem	Through	900	1,2-5,11
		Circumfer- ential	5600	11
32	Lynn	Inward	1220	1,2-6
	Marblehead			
	Nahant	Core	7070	1,2-6
	Swamscott	Through	1600	1,2-6
		Circumfer- ential	2700	22
31	Lynnfield	Inward	740	1,2-6
	Saugus	Core	8670	1,2-6
		Through	2000	1,2-6
		Circumfer- ential	3300	22
14	Revere	Inward	900	1,6,25
	Winthrop	Core	9790	1,6,25
		Through	2700	1,6,25
		Circumfer- ential	2000	23,24
13	Chelsea	Core	10780	1,6
		Through	2100	1,6
		Circum-	2600	24

FIG. 5.4 NORTH SHORE CORRIDOR A.M. PEAK TRAVEL




	<u>Cities</u>	<u>Direction</u>	<u>Cum. Trips</u>	<u>Likely Routes</u>
35	N. Reading	Inward	8200	10,13
	Reading	Core	2600	10,13
	Wilmington	Through	600	10,13
30	Melrose	Inward	8100	10,13,9
	Stoneham	Core	5760	10,13
	Wakefield	Through	1400	10,13
29	Burlington	Inward	4700	10,12,13,14
	Winchester	Core	4810	10,12,13,14
	Woburn	Through	2300	10,12,13,14
16	Medford	Inward	1500	10,12,13
		Core	13,420	10,12,13
		Through	2700	10,12,13
15	Everett	Core	16820	9,15
	Malden	Through	4000	9,15

FIG. 5.5 NORTH CORRIDOR A.M. PEAK TRAVEL

	<u>Cities</u>	<u>Direction</u>	<u>Cum. Trips</u>	<u>Likely Routes</u>
39	Dover Medfield Millis Norfolk Sharon Walpole	Inward Core Circumfer-	7500 2100 750	10,18,20-22 10,18,20-22 10
24	Needham	Circumfer-	2900	10
23	Canton Dedham Norwood Westwood	Inward Core Circumfer- ential	4900 2480 1750	10,18,20-22 10,18,20-22 10
8	Jamaca Plain Roslindale Hyde Park West Roxbury	Core	7420	19,21,22

FIG. 5.6 SOUTHWEST CORRIDOR A.M. PEAK TRAVEL



	<u>Cities</u>	<u>Direction</u>	<u>Cum. Trips</u>	<u>Likely Routes</u>
41	Duxbury	Inward	5400	16-18
	Hanover			
	Marshfield	Core	1930	16-18
	Norwell			
	Pembroke	Through	500	16
	Rockland			
40	Cohasset	Inward	5300	16-18
	Hingham			
	Hull	Core	4850	16-18
	Scituate			
	Weymouth	Through	1200	16
22	Braintree	Inward	6500	16-18
	Holbrook			
	Randolf	Core	7690	16-18
		Through	1900	16
21	Milton	Inward	6500	16-19
	Quincy			
		Core	12720	16-19
		Through	3700	16
9	Roxbury	Core	20060	16, 17, 19
	Dorchester			
	Matapan	Through	4800	16, 17, 19

FIG. 5.7 SOUTH SHORE CORRIDOR A.M. PEAK TRAVEL

inbound trips from Zones 33 and 34. Total trips are at least 30,000 and the highway capacity is approximately 10,000 vph. I-93 and Rt. 28 will have to share an additional 16,810 trips with Rt. 38. The additional capacity is 1,100 vph. The total requirement is up to 46,810 trips with a total capacity of 11,100 vph. These systems will operate at very high volume to capacity ratios. From Zone 16 inbound I-93, Rt. 28 and Rt. 28 would be saturated, which is currently the case. Traffic densities (K) exceeds the K at maximum capacity. From Somerville into the city's core the traffic is very slow and often stop and go as the survey predicts. Traffic profiles on Rts. 1, 1A, 107 and 99 indicate the number of lanes are adequate, but engineering work such as optimizing traffic signals and reducing key grade crossings would adequately serve these highways.

The northbound traffic flow is summarized as follows. I-93 to the junction with Rt. 3 has a demand of at least 5,400 vph in the morning peak hours. This is addition to the northbound traffic from I-95 that is diverted eastbound. I-93, Rt. 1, Washington St., Rt. 138 and Rt. 28 have to share 16,930 trips in the A.M. peak up to Zone 23. The capacity is 11,370 vph, which should be adequate in an optimal system. From Zone 23 inbound there are 24,900 trips with a system capacity of 6200 vph. This is inadequate and flow improvements may have to be made. Otherwise, Zone 23 and 39 traffic will opt to travel I-93, adding to the saturation problem. Rts. 3 and 53 will share 17,480 trips with a

capacity of 7,130 vph. From Zone 22 into the core I-93, Rt. 3A, Dorchester Ave. and Blue Hills Ave would share 65,260 trips. Total capacity is 11,300 vph and the highway system would be saturated. This is the problem currently experienced on the Southeast Expressway and the Central Artery. The proposed Central Artery depression would add a maximum of 4,000 vph to the current 11,300 vph capacity giving a total of 15,300 vph. Even if the A.M. traffic loads were spread over a four hour peak period evenly, there is still a requirement for 16,315 vph. Therefore, it is concluded that there is a need to improve and expand the system, plus encourage car pooling and mass transit use.

5.3 FORMAT FOR APPLYING THE MODEL

Applying the rules of economic efficiency would require a large data base and computer applications. Foremost among the data requirements is the need for good travel information. Second, is the requirement to compute the construction and land costs for each road. Costs that have been paid (sunk costs) need not be recouped. However, the portion of these costs that are owed through bonds, grants or other forms of government borrowing needs to be figured into the pricing formulas. There should also be good records kept on the per mile costs of maintenance for each road. A highway inventory needs to be taken to determine that level of 3R work required and when this work should be scheduled for each road. Finally, each city should assess the worth of each road

passing through their area. The benefits based on the increase in property tax assessment and taxes generated from businesses should be weighed against the costs to each neighborhood of the road. For residential areas the following procedure is recommended to determine the associated highway costs. First, a property value gradient should be drawn up from the edge of each road under consideration. An increase in property values indicates the market places a premium on living away from a major thoroughfare. This in itself is not enough. The rate of return on property values must also be considered. An owner may sell a home adjacent to one of these highways at a lower price, but the owner may have also purchased the home at a lower price. Likewise, the rent may be lower near the road, but the purchase price to buy the rental property may also be lower. If there is in fact a loss in investment return, then this would be an actual cost of the highway. Therefore, the city must weigh the loss in property taxes due to the existence of the highway against the social benefits from rental and property purchasing price savings. In addition, the social benefits of the highway for fire and ambulance services and travel time savings to the city have to be considered. The net cost would determine the annual road rent to be paid. It is worthwhile noting that the city of Boston has a problem with a high number of commuters consuming the city's services but paying their property taxes elsewhere. This problem is compounded by the fact that Boston has a large amount of tax exempt property.

The highway system in Boston falls under the ownership and operation of the Boston Public Works Department, the state which is responsible for about 38 miles of expressways and the Metropolitan District Commission which controls 35 miles of parkways. (2:22) The urban highway planning and control should be consolidated under one agency and the information on the system should be placed in one database. The effectiveness of this approach has been demonstrated in Dallas, Texas where the city is responsible for all main components of the capital infrastructure which includes streets, bridges and mass transit. (4:xiii) Each summer city engineers survey Dallas's streets and each street is given a rating. This information is used to plan for maintenance, resurfacing and to justify the city's budget requests for streets and highways. (4:8-9) The report is made public annually and voters are kept up to date and informed of the city's highway needs. As a consequence, Dallas has been highly successful in getting bond approvals and the city planners have been able to channel a substantial share of its general federal aid into the capital budget. (4:ix-xiv)

Secondly, in order to apply the investment rules of economic efficiency, good travel information is essential. The state should require all businesses to report employee addresses. This could be a simple report that gives the number of employees commuting from the neighboring cities. This information could be submitted biannually or even every leap year and still give reasonable information. The

off peak hour traffic data could be collected using surveys of parking lots and color aerial photography.

Finally, a regional survey of highway conditions, such as the Dallas survey is important and should be added to the database. Once the consolidation of planning and control of the regional highway is complete and the database is established, the investment and pricing model can be applied.

Section 5.2 showed that based on 1977 information that more lane capacity is required to handle peak hour traffic on the Central Artery. However, this fact is not conclusive until simulation models of optimal peak load pricing is applied to the system. Button points out that desk top simulations have shown that road pricing reduces congestion on the order of 25-40% and that real world applications in Singapore reduced traffic levels by 22%. (3:79-76) A 25% reduction in the predicted 1980 traffic loads entering Boston from the South would result in a traffic demand of 12,240 vph if the demand were evenly spread over the A.M. period. This is 4,000 vph less than the requirement without optimal peak load pricing, assuming the system were efficient.

Setting up the computer models will be discussed next. This process involves the determination of the annual loading periods, converting vehicle demand into homogeneous measures of vehicle units and ESAL's and determining a starting point for all system costs.

First, an applications program would act on the database to generate a daily graph such as that depicted in Fig. 3.5.

This graph would be divided into the demand periods τ . The weekend traffic loads would not produce the same type of graph, but it could be expressed in terms of the weekly flow. For example, the peak flow on Saturday may be equal to the noon flow during the week. The year is then divided into T total periods.

Next, the traffic density must be expressed in terms of vehicle units. For example, the effects on density, headway and speed are not the same for cars and tractor trailers. The Transportation Research Board recommends the following passenger car equivalent (PE) on level terrain for multi-lane highways; a) trucks = 2 PE, b) busses = 1.6 PE and c) recreational vehicles = 2 PE. For two laned highways at low volumes all the above vehicles equal three PE, while at high volume to capacity ratios they equal two PE. (1:261)

Section 3.2 demonstrated how a highway is designed around a finite number of ESAL's. The total costs for construction, maintenance and rehabilitation that is based on loading conditions during the road's life can be divided by the total design ESAL's to give a unit price per ESAL. Each vehicle can then be charged for their loads based on their ESAL consumption. The formula would be;

$$\text{Charge} = \$/\text{ESAL} \times \sum_i F_i \cdot n_i \cdot A_i$$

Where F = ESAL conversion factor (Table 2.2)

$n_i A_i$ = Number of axles in weight category i .

In the absence of weighing facilities the trucks could be charged on the basis of maximum expected weight. Random weighing by law enforcement officials using portable scales could be used to enforce the maximum weight standards. Such a rate schedule would encourage truckers to consolidate loads into fewer trips. Current technology allows trucks to be weighed without stopping. The Pennsylvania Turnpike employs a scale which weighs each truck axle while the truck is rolling 5 mph, and by the time the truck reaches the toll booth a computer has printed out a card that has the charges for the vehicles loads. The system is coded by vehicle class. Such a system could be used on all Category 1 highways. Finally, many commercial trucks are required to have tamper proof hubdometers bolted to their rear wheels. This device registers the trucks mileage and the annual mileage could be recorded for tolling purposes when the truck owner applies for his or her annual license.

The last step in setting up the model is determining the program starting point. Since the planners are dealing with a system in place, they have to determine or estimate how much life is left in the roads. If unknown, the original design ESAL's could be determined by backing into the problem from known existing conditions such as pavement and base thickness. Then, estimates of traffic flow since the road was opened would have to be made to determine what portion of the original design ESAL's was left. The original land and construction costs may have been paid for, and if so, they should be subtracted out. Once the starting point is

established, the future costs of each road would be determined. The traffic engineers would determine which processes would be applied and the cost of application. For example, the interchange at the junction of I-93 and Rt. 1 currently forms a bottleneck, because traffic from Rt. 1 has to cross I-93 in a space of less than a mile. At high traffic densities this causes the traffic on I-93 to grind to a stop. The same situation occurs where the Callahan and Sumner Tunnels junction with I-93. Process R_2 would be appropriate here. The same process would be applied to all roads where there is a preponderance of grade crossings. The entire process would be iterated using computer simulation and the pricing formulas developed in Chapter 4. The results would provide planners with the appropriate investment plan based on optimal peak load pricing and economic efficiency.

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CHAPTER 6

COMMENTARY ON PROGRAM

6.1 SUMMARY

This thesis established the fact that there is a big highway infrastructure problem, because many miles of U. S. highways were built in the post WW II era and this mileage is reaching the end of its design life. In addition, it is evident that the original travel forecast were inadequate, leading to many areas of congestion and, in view of the growth in the heavy trucking industry, pavement overloading. However, the system does not have to be built in its entirety. Much of the required land has been purchased. It will not be necessary to replace all of the roadbeds. Certain areas of design uncertainty and deficiencies have surfaced during actual operation and can be corrected so that future uncertainty is reduced.

It was also shown that roads and highways have a finite life, and this measure of design life can be put in terms of demand where a predicted volume of traffic and traffic mix can be used to determine how the road will last. This also give a means to charge traffic based on actual loading costs.

These problems of infrastructure decay and highway loading were incorporated into the established theory of optimal highway pricing. In particular, the variable costs were shown

to be a function of user loading conditions as well as the effects of user demand on time and vehicle operational costs. These conditions established the long run investment criteria for highways.

It was also shown that agencies responsible for building highways provide three products to society. They are speed of travel, highway capacity and highway engineering. All three affect demand, efficiency and costs, and the value of all three products must be closely examined to determine the levels of output of each of these products. The combination of these products ultimately determines the level of service of a highway.

Finally, an urban highway system offers many opportunities for investment in many different route alternatives. Investing in one category at the expense of all of the other categories may not solve the system problems of congestion and may be very inefficient. As was demonstrated in Chapter Five, on the surface it appears that the proposed Central Artery improvement project may not relieve the current congestion problem.

6.2 REAL WORLD PROBLEMS

Perhaps the greatest problem facing the implementation of optimal pricing schemes for highways lies in political and public resistance to raising the cost of highway use. This is true for several reasons. First, there is a tradition of the federal government providing free highways. In the nation's early history, every male citizen had an obligation

to either personally provide annual road work or pay someone to work for them. This gave the nation's citizenry a collective sense of the cost of providing public roads. As highway technology became more complex this old system gave way in the late 1800's and early 1900's to government supported highway construction and maintenance. Highway funds have been raised through property taxes, fuel taxes, excise taxes on tires and auto parts, and from the general tax revenues. This has amounted to spreading out the burden and in effect subsidizing roads. The result has been to alienate the users from the true costs of highway transportation. It has also been the policy of federal government during the development of the interstate highway system to eliminate, when possible, toll roads. As a consequence users may not actually fully perceive the actual costs to society in wasted fuel, extra pollution and wasted time. These factors all lead to a resistance of increasing individual users costs even though society as a whole may gain.

Another problem in an urban system would arise if there is no linkage between highway construction and urban development. If an urban area allows the development of businesses and offices, it must also account for the impact on the traffic system. An area of travel concentration, or node, must be able to absorb traffic at the same rate as the urban traffic supplies vehicles. Supplying adequate parking is not enough. Vehicles must be able to reach this parking at an adequate rate, or the highway system will become bottled up.

In section 4.4 three broad assumptions were made to generate the pricing formula and apply the rules of economic efficiency. First, it was assumed that there was a means to control driver behavior. Secondly, it was assumed that an urban highway system was comprised of equally competitive routes. Finally, it was assumed that drivers have enough information to select the route providing transportation at the minimum cost. Each of these assumptions will now be addressed.

The determination of marginal costs can be made through computer formulation, but collecting tolls for these costs is not possible on all road categories. Tolling on category one highways based on demand and weight is possible. The limited and uncontrolled access highways present the problem. If tolling is done on category one highways only drivers may indiscriminately divert to other routes and overburden their capacity. The objective is to change driver behavior by making drivers take a trip only if its benefits exceeds the true social cost. There are other means besides tolling to do this. First, vehicles entering a road at certain hours could be required to display a special prepurchased pass, the price of which is based on the highway pricing formula. Drivers using toll roads could display a toll ticket or use the tickets to purchase passes. Parking lots could be required to charge higher fees during peak hours, and private parking areas would have to pay this fee as well. Businesses would have to provide non-traffic obstructing loading areas

or pay a fee to have street deliveries during peak hours. Out of state and nonresident trucking would have to purchase a pass at designated areas prior to entering a node. They would be charged based on vehicle units and maximum weight unless they produced a certified weight ticket showing the actual weight. In some areas trucking may be excluded during peak hours, but this policy has to be carefully evaluated since it could have national implications. For example, an out of state produce truck may have a certain delivery time window to meet. Incentives could be offered for carpooling, such as eliminating the special pass requirement. High occupancy vehicle lanes (HOV) may not prove to be effective. Most mornings the HOV lane on I-93 south into Boston runs well below capacity, but that is in the absence of tolls or other pricing techniques to encourage carpooling.

It was also assumed that travel between nodes of concentration could be made on several equally competitive routes. There are several issues that may create problems with this assumption. First, is the effect of route separation. How far does a route have to be separated from another route to discourage drivers from using it? The key to answering this question is the ability to access each route. If a driver finds one route congested he or she will use another route if can be accessed easily. This may not be a problem for the knowledgeable driver, but will be difficult with drivers unfamiliar with the system. One solution is to provide commuter highway systems maps similar to the mass transit

maps and to provide good route linkups. The second issue concerns the impact of other city streets on the system. These streets were ignored in the analysis. They could feed the various routes with short haul trips that could snarl traffic. The use of special passes on selected routes during peak hours may prevent this. The traffic data presented in Chapter Five ignored the large volume of interzone traffic. Again, this presents the same type of problem just raised. This traffic would have to be accounted for in addition to the special pass program. The requirement for special passes may be undesirable for local citizens, but the inconvenience is reimbursable through the annual rent cost provided in Equation 9 of Chapter Four.

Finally, it was assumed that drivers would have enough information to make the optimal choice of route based on the route's price. This is currently not a true assumption, but technologically feasible. In Chapter Four it was shown that the measure of traffic flow and density for freely flowing traffic could be derived from the traffic speed. The same could be measured on all categories of highways using different formulas. The speed could be measured with remote radar and the information displayed at intervals along the each route through telecommunications. System information could be fed into a central computer which could also display information about alternative routes. A typical display is envisioned as;

"AVERAGE SPEED ON THIS ROUTE IS 35 MPH"

"SUGGESTED ALTERNATIVE ROUTES ARE"

"RT A - AVERAGE SPEED IS 45 MPH"

"RT B - AVERAGE SPEED IS 48 MPH"

"TOLLS ON RT C ARE \$.35 PER MILE - SPEED IS 50 MPH"

Finally, information on optimal routes could be given to radio stations providing traffic reports. The cost of this information system would be included in the road price, but the system only needs to operate during peak hours.

The pricing formula does not handle the growth in traffic over a long period of time. Rather, it has to be assumed that market equilibrium over the long run has been reached. This of course, is not true over the entire life of the road, so investment decisions have to be based on a shorter period. The major problem with this is by shortening the long run period, economies of scale in highway construction may be lost.

The pricing formulas are all based on a first best economic world, with assumptions assuring these conditions are met. It is possible to comply with these assumptions, but in their absence, the model would be applied in a second best world and the model may not work.

6.3 CONCLUSION

Optimal highway pricing and investment has not been applied in this country. Part of the reason is technology. The database required and mathematical work needed to determine investment and pricing levels for an urban highway system

would have been overwhelming in the past. The information requirements mentioned in the previous section would have been very expensive and probably impossible to acquire in a reliable fashion. The technological advances in computer processing is making the real world application of optimal pricing possible. Hong Kong has implemented a test program in which an electronic system scans, from remote sensors, a special plate attached to each vehicle. This plate number is sent to a central computer, and at the central processing unit, the plate information is matched to the vehicle owner and the current optimal toll is charged. The owner receives a periodic billing for these tolls. (1:77)

The Singapore plan is another example of applying the theory in actual conditions. It is possible that further applications will be seen throughout the world. If these results are favorable, then it is very likely that the same application of the theory of optimal highway pricing will be used in the United States.

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